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TIDAL RIVERS

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(1) HYDRAULICS
(2) IMPROVEMENT
(3) NAVIGATION

BY

W. H. WHEELER, M.Inst.C.E.

AUTHOR OF
'THE DRAINAGE OF FENS AND LOW LANDS BY GRAVITATION AND STEAM POWER'

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THE DEVELOPMENT OF HYDRAULIC SCIENCE.

Theory of Hydraulics.—The commencement of the study of the laws which govern the flow of water, and of its effect in eroding the banks of the channel through which it passes, and in transporting or depositing the material eroded, may be said to date from the middle of the sixteenth century, when Galileo applied his discovery of the laws of falling bodies to the movement of water, and traced the connection between the universal law of gravitation and the tides of the ocean. About the same time Toricelli showed the analogy between the discharge of water from orifices in vessels and its velocity in open channels, and proved that this was due to the acceleration caused by the slope of the surface of the water.

Bartolotti, an Italian engineer, having projected a plan for improving the river Biscozio, Galileo wrote a treatise exposing the errors of this scheme, based on the above principle, that the motion of water is regulated by the inclination of the surface, and not by that of the bed of the stream.

In 1661, the Abbot Castelli devoted his attention to the movement of water in open channels, and to the effect of tidal action on the discharge of rivers at their outfalls. The result of his observations was published in a treatise entitled "The Mensuration of Running Water." An English translation of this treatise was made by T. Salusbury, and published in London in 1661. Castelli laid down the following laws as the result of his researches:—

That the velocity of the water in a river is derived from the pressure of the upper water. That in a river reduced to a state of permanence the quantity of water which passes through all its sections in equal spaces of time will be equal. That the medium velocities in the different sections will be reciprocally proportional to the amplitude of the sections. That

if a river flowing in a rectangular channel with a certain velocity be increased by a flood to double its height, the velocity of the water will become double. On this ground he condemned attempts to mitigate floods by diverting the water of the rivers into new channels.

Castelli also investigated the cause of the formation of bars at the mouth of rivers entering the sea. The range of tide being very small in the sea which came under his observation, his experience was limited. The opinion which he deduced from watching the outfalls of the rivers into the Mediterranean was that the sea, disturbed by the winds, raised the sands at the bottom, and these were carried by the flood-tide into the mouth of the river; that the detrital matter brought down by the river and the sand driven back into the sea by the ebb, being discharged at a point where the sea and river met with equal force, settled and formed a bar.

Towards the end of the seventeenth century, considerable damage was constantly happening from the incompetence of the rivers of Italy to discharge the water brought down in floods. The governments of Rome and Florence appointed several commissions of engineers and mathematicians to consider the general laws of hydraulics, and how these could be best applied to the regulation of the rivers and the prevention of floods. At one of these commissions, appointed by Pope Innocent XII. in 1693, to investigate the condition of the rivers passing through Bologna, Ferrara, and Romagna, Bologna was represented by an engineer named Guglielmini. As a commissioner he spent a great deal of time in investigating the conditions of the rivers and the manner in which the water was discharged. The result of these investigations was published in 1697, in a book entitled "Natura de Fiumi." Several chapters of this book are devoted to the flow of water in rivers, and its motion down inclined planes. He shows that an equilibrium becomes established between the force of the currents and the resistance from the friction on the bed and sides of the channel. That motion is due to surface inclination, the upper layers of the water pressing on the lower layers, and that movement depends on the pressure, which acts more and more as a cause of movement as the stream deepens. That the slope of the bed of a river will diminish as the volume of water increases. That as rivers recede from their sources the inclination of the bed will

diminish, and the size of the material transported will also diminish in a corresponding ratio. That where two streams, equally turbid, united in one common channel, the velocity being as great or greater than before, the material would still be kept in suspension, and the common bed would be eroded and maintained, although its inclination be less than that of the tributaries. That a stream, if not guided by artificial means, will assume a series of curves. That where erosion once commences in a channel, in a part where the earth has less tenacity than in other parts, the points and angles of the part eroded will be washed away and a concave surface formed; the deflection of the stream caused by this will strike against the opposite side of the channel, causing an erosion on its banks, and then a series of curves will go on forming until the resistance becomes equal to the force and an equilibrium is established. That, other circumstances being equal, the larger the rivers the more considerable will be the circuit of their windings. That bends are first caused by irregularities in the composition of the soil of which the channel is composed, or by obstructions which the water encounters in its flow. That if two rivers similar in section and velocity enter the sea separately, the sum of their sections will be greater than the section of the two streams united in one channel. That the flow and reflow of the tidal water help to maintain the mouths of the rivers free from deposit. That the form of the mouth of a river entering the sea will depend upon the difference of velocity between the river and the tide-currents. That the material brought down by rivers will settle along the eddy part of the shore and form sandbanks, which will go on gradually increasing and oppose the outflowing water from the river according to the direction of the tidal current.

Applying these laws to the rivers of Italy, he advocated that it was better to unite all the streams of a district into one main trunk rather than to allow them to run off in several smaller channels. He advised great caution in carrying out works for shortening the rivers conveying gravel and other material by cutting off bends, and that before making such cuts a perfect knowledge of the soil through which the river passed should be obtained, and also of the conditions under which the existing equilibrium had been attained.

Notwithstanding the advice given by these commissions and

works carried out on their recommendations, the Po and the Reno, being obstructed by the material brought down from the higher country, continued to break their banks and to flood the plains of Bologna. In 1760, Paul Frisi, a professor of mathematics at the University of Turin, distinguished himself in the controversy then going on as to the best means of regulating these rivers. In 1762 he published a treatise on rivers and torrents, which also has been translated into English. Frisi, in the first part of his book, treats very fully on the cause and origin of rivers, and the different effects produced by water carrying gravel and sand. He analyzes the theories of previous writers, and treats of the slopes and velocities of single and combined streams. He suggests that the slope of the bottom of a channel contributes principally to the acceleration of the stream in the primary beds in the bosom of the mountains where the height of the body of the water is very small, and where the fall is very rapid. He dealt with a proposition which had been put forward about this time by Genneté, that a river may absorb the whole of the water of another river of as great magnitude as itself without producing any sensible elevation in its surface—an opinion which he attempted to support by numerous experiments and by pointing to the Rhine, which received the Mainz, whose flow of water was nearly as great as its own, without it being possible to observe any perceptible difference in the dimensions of the bed; also to the Moselle, which is absorbed with the same effect; and in the converse case, where the Rhine divides on entering Holland without its surface being apparently lowered. Remarking on the experiments which had been made by Genneté on an artificial watercourse, he says that, although such models may not serve as a guide for the regulation of great rivers, they may yet be sufficient to show that nature on a small scale, as also on the greater found in rivers, always acts by the same laws. That it appeared to him, both from the result of these experiments and also from his own observations of the rivers of Italy, "that there frequently is not any sensible increase in height even when there is a considerable augmentation in the quantity of water; and therefore that the velocity of the water increases sensibly in the same ratio as the quantity," and that the velocities of united rivers increase nearly in proportion to their volumes. He compares the propositions laid down by Gugliemlmini as to the effect of the transporting and

eroding power of water in rivers with his own observation and experiences, and asserts that the bottom of a main stream will be equally established above and below its junction with a tributary if the sines of the slopes are reciprocally in proportion to the quantities of water.

He also deals with the effect of the tides in keeping open the mouths of rivers. He considered that although the rise and fall of the tides in the Mediterranean were very small, yet they had a material effect in keeping open the outfalls. He points out that the bed of the river Po was seven feet lower at fourteen miles up its course than at its entrance into the Mediterranean; and the Primaro and other rivers had like concavities in their beds, which maintained themselves open notwithstanding the large amount of sediment brought down in floods. He quotes the following reduction of the ideas of Guglielmini to the propositions made by G. Manfredi, to the effect that the constant submersion of the whole bottom below the level of the lowest ebb maintains the matter always in a detached condition and keeps it saturated with water; that the current of the flood-tide keeps the particles of sand and earthy matter raised from the bottom; that this current, setting against the stream of the river, raises its surface two or three feet more than the ebb requires, and then the ebb current, being stronger than that of the flood, contributes to increase the agitation of the water, and keeps the particles of sand incorporated with them, and so prevents them settling and raising the bed. In treating of the means necessary to prevent the erosion of the banks of rivers, he advises that, when groynes are used to prevent erosion, they should extend out from the bank of the river in a direction so as to make with the bank half a right angle. He argues in support of this by showing that, if the direction of the water is parallel to the banks, by resolving its velocity into two others, the one at right angles and the other parallel to the spur, the latter velocity will be proportional to the cosine of the angle which the spur forms with the bank. Then, further, as the quantity of water that impinges against the spur is proportional to the perpendicular drawn from the outer extremity of the work to the bank or to the sine of the same angle of inclination, the quantity of motion with which the stream will flow in a direction parallel with the spur towards the opposite bank will be as the product of

the sine into the cosine of the angle which the groyne makes with the bank, and since this product is a maximum when the angle is half a right angle, it follows that the most advantageous position which can be given to the groyne is that in which it forms with the bank an angle of forty-five degrees. He goes on to point out that it is not possible to prevent the water from scouring deep holes in the vicinity of groynes, and therefore advises, as a more reliable course, that works of protection should run parallel with the banks, and the resistance be thus uniformly distributed.

In 1765, Paul Lecchi, a Milanese engineer extensively engaged on canal work, published a book containing a complete examination of all the different theories relating to effluent water, and endeavoured to show how such laws applied to water in rivers and canals.

A few years later, the Abbé Bossuet undertook a series of experiments for the French Government, and published the result in a treatise on the general principles of hydraulics and the effect of friction in retarding the flow.

In 1779, Dubuat, following up the researches made by his predecessors, commenced an examination into the laws governing water when running in open channels made in clay, sand, and gravel, and also into the varying effects of piers, sluices, and other obstructions. From these experiments, conducted at the expense of the French Government, after the labour of ten years, he obtained a sufficient knowledge of the velocity of the different parts of a uniform current, and of the relation of the velocity at the surface and at the bottom and sides, and the resistance from different kinds of soil, to enable him to reduce these to algebraic form. In 1786 he published his "Principles d'Hydrauliques," in which he gave the theories and the result of his experiments. Dubuat contended that, as the motion of water was due to the action of gravity, and being in a perfect state of fluidity, if it ran in a bed from which it experienced no resistance, its motion would be constantly accelerated like the motion of a body descending an inclined plane. As, however, the velocity of water in a running stream is not accelerated indefinitely, but arrives at a state of uniformity, there must exist some obstacle which checks the accelerating force. This obstacle he traced to the resistance experienced by the particles of water coming in contact with the bed and sides of the channel, or to the viscidity

of the water, from which he deduced the following law: That when water runs uniformly in a channel, the accelerating force is equal to the sum of all the resistances which it experiences; gravity being the accelerating force, and the resistance of the sides and bottom of the channel the modifier. To obtain the relation between the rubbing surface and the water, he reduced every section of the various-shaped channels on which he experimented to a rectangular parallelogram of the same area, and having its base equal to the border unfolded in a straight line. The product of this base by the height of the rectangle being equal to the area of the section, this height or depth was a representative of the variable ratio of the section and of the border, and was termed, "*The hydraulic mean depth.*" He further showed that, as the velocity of the water in an open channel is proportional to the square root of the mean radius of the bed, therefore a trapezium in which the breadth at the bottom is two-thirds of the depth of the water, and where the slope of the sides is four-thirds of the depth, would give the least resistance.

Chezy, an engineer of the Ponts et Chaussés in France, following on the lines of Dubuat, determined the relations existing between the inclination, length, transverse section, and velocity of water flowing in open channels.

Having determined that the resistance which water encounters in moving in an open channel is proportional to the wetted perimeter, and to the square of the velocity plus a fraction of the velocity, and is in inverse ratio to the section, he deduced the following formula:—

$$V = \sqrt{R \times S} \times C$$

in which V = the mean velocity.

R = the hydraulic mean depth or radius.

S = the sine of the slope or the fall divided by the length.

C = a constant determined by experiment.

The value given by Chezy to the constant C is not known. Although a great many attempts have been made to determine this value, and also to devise a formula which will adapt itself more readily to the varying conditions under which water flows in open channels, as a matter of fact the relations between the accelerating and retarding forces as algebraically settled

by Chezy are universally acknowledged up to the present time as sound, and as affording a practical method of obtaining the velocity of running water.

In 1779, the Abbé Mann contributed a treatise on rivers and canals to the *Philosophical Transactions* of the Royal Society of London, in which he made known to this country the works of the Italians, and recapitulated many of the principles laid down by Guglielmini relative to the acceleration and retardation of water flowing in rivers.

At the beginning of the present century, M. Girard, engineer of the Canal l'Ourcq, and M. Prony conducted a large number of experiments, and published several papers on the theory of running waters. The former especially investigated the retardation of the velocity due to obstruction from weeds and other similar causes. To meet cases of this kind, he proposed to amend the formula of Chezy by multiplying the perimeter of the channel by 1·7.

In 1798, Venturi of Modena published a treatise on the lateral movement of fluids. In this treatise he examined the causes of eddies in rivers. He showed that every eddy destroys part of the moving force of the current, and that the retardation of the accelerating motion is due not only to friction over the bed of the stream, but also to eddies produced from the irregularities of the surface and in the direction of the channel, a part of the current being employed in restoring equilibrium of motion.

In 1801, Eytelwein published his "Handbuch der Mechanik," in which, besides treating generally on the flow of water, and endeavouring to simplify the theory of the motion in rivers, he reiterates the theory previously set up by Genneté, that a river may absorb the whole of the water of another river equal in magnitude to itself without producing any sensible elevation in its surface.

In 1820, M. Fontaine, an engineer employed by the French Government to carry out works for regulating and restraining the Rhine at that part where it passes through French territory, in order to arrive at a satisfactory plan, carried out a series of investigations as to the flow of water under various conditions, the result of which he published in a work, "Travaux de Rhine." In this work he lays down the following principles as those to be observed in regulating and controlling a river, and which he

took as his guide in designing the works for the rectification of the river :—

That all secondary branches should be closed, and the waters united into one channel. That rectilinear cuts should be avoided, and the channel be conducted by a series of curves, the determination of the radii of which should be derived from observations on the rivers to be dealt with. That the areas of the channels should correspond with the different volumes and velocities of the water. He contended that the advantage of the curvilinear direction arises from the fact that the force of the centrifugal projection of the current on the concave side of the river can be more easily counteracted. The proper determination of the radii of curvature, he considered, depended on the inclination and force of the currents. In the case of the Rhine, he settled the maximum lengths of the radii at 7250 feet where the depth in the curved part of the river was 50 feet; and where the depth did not exceed 36 feet, 4000 feet. His observations on the velocity of the water in the Rhine led him to the conclusion that the greatest velocity is at the surface. That the velocity, which at first diminishes insensibly downwards, decreases rapidly towards the bottom in a ratio dependent on the nature of the bed. He also found that the surface of the stream varied between convex, concave, and horizontal, as the river was either rising, falling, or slack.

His velocity observations were made by a Woltman current-meter, checked by floats.

A very valuable addition to the development of hydraulic science was made by the articles written for the "Encyclopædia Brittannica," about the beginning of the present century, by Robison, on "The Theory of Rivers;" by David Stevenson, on "Rivers;" and by Thomas Stevenson, on "The Construction of Harbours." Mr. Robison also dealt with the same subject by an article in his "Mechanical Philosophy."

In 1833, Mr. George Rennie made an interesting and valuable report on "The Progress and Present Knowledge of Hydraulics as a Branch of Engineering," to the British Association Meeting at Cambridge; and in 1834 a second report on the same subject.

In 1835, a work was published ("Recherches Hydrauliques") by two French engineers, Messieurs D'Arcy and Bazin, in which is recorded the result of a number of experiments made in artificial channels constructed of different materials and varied

in form, the results being compared with observations made in rivers and canals. From the data thus obtained an endeavour was made to produce a coefficient for C in the formula of Chezy, $V = C\sqrt{RS}$. The coefficient so found was made to vary with the values of the hydraulic mean radius (R) and with the conditions of the section, these conditions being arranged in four categories, the last of which only applied to sections in earth and rivers. The determination of this coefficient, which is given in the Appendix, although approaching nearer to general accuracy than those previously in use, is not applicable to large rivers having low inclinations.

The Tide and Waves.—The theory of the tides is a subject which has hardly received the attention which it deserves. The result of the observations made by Pytheas, a Greek merchant and philosopher, who resided at Marseilles, and had often been to Great Britain on visits to the tin-mines, is recorded by Plutarch and Pliny, and this constitutes all that was known on the subject by the ancients. Pliny ascribes the moon as the source of the tides, and infers, from the gradual change of the tides between the new moon and the quadrature, that the sun was not unconcerned in the operation. He also records that the tides gradually abated from the times of new and full moon to the quadratures, and then increased again; and also that the greatest tide was always some time after the new or full moon, and that the smallest was as long after the quadratures. He also observed that the retardation of the tides from day to day was greater when the moon was in quadrature than when new or full.

Very little further progress appears to have been made to a more accurate knowledge of this subject until the time of Galileo in 1624, when he published a treatise on the theory of the tides, founded on his previous discovery of the revolution of the earth. The Church, basing its knowledge of science on the wording of the Scriptures, had decreed that the world was the centre of the universe, and that the sun and other planets revolved round it. As Galileo's theory was at variance with this, and depended on the revolution of the earth, the work was suppressed as repugnant to the holy Scriptures.

In 1740, D. Bernoulli wrote a dissertation on the tides, which shared with McLaurin and Euler the prize given by the Academy of Paris for the best essay on this subject. The more accurate knowledge of the law of gravity as formulated by

Isaac Newton laid the foundation for the theory as to the cause of the tides which is adopted by astronomers at the present day. The subject was further elucidated by papers contributed to the *Philosophical Transactions* by Wallis and Flamstead, and by Whewel and Lubbock in 1833 and 1836, and by the article by Airey on Tides and Waves in the "Encyclopædia Metropolitana," and by Darwin in the "Encyclopædia Brittannica." Considerable light as to facts relating to this subject was obtained by a committee of the British Association on tidal observations between 1868–76; on tidal observations in the Humber, the Ouse, and the Trent in 1864; in the Mersey in 1875; in the North Sea in 1878–86; on the Harmonic Analysis of the tides in 1883–5; and on Tidal Models in 1889–91.

An investigation into the theory of the formation of waves was undertaken under the direction of a committee of the British Association by Scott Russell in 1836. After carrying out a great number of experiments two reports were produced, dealing with the great tidal wave of the ocean and the waves of oscillation and translation. The laws laid down in this report have ever since been accepted as a correct definition of the subject.

Although the general laws relating to the tides were thus made known from early times, no collection of observations existed of sufficient extent to enable tide tables to be compiled for use at the different ports of the kingdom, or which would afford information to mariners voyaging to foreign ports. To meet this want, at the request of the Academy of Paris, the French Government instructed the officers at the ports of Brest and Rochefort to keep a register of all the phenomena relating to the tides and report it to the Academy. These observations, kept up continuously for several years, were analyzed by Cassini, and from them he deduced a general law for the calculation of the tides.

In 1839, the French Hydrographic Department directed M. Chazallan to prepare tables giving the height and time of the tides at the principal ports in France, and the "Annuaire des Marées des Côtes de France" is now issued annually, giving not only this information, but also constants by which the time can be ascertained at other ports not given in the tables.

A daily record of the tides has been kept at all the principal ports of this kingdom for a long series of years, and there is

prepared and issued by order of the Admiralty annually "The Tide Tables for the British and Irish Ports." This book gives the times and heights of high water for night and morning of every day for twenty-three representative ports in this country, and also the time and height of the tides at full and change for all the principal ports in the world.

Navigation.—At the end of the thirteenth century, the invention of the mariner's compass by Fluvio Giolia, of Amalfi, had enabled mariners to extend their voyages to distances beyond the coast-line with some confidence.

The long voyages in unknown seas made by Columbus, Baffin, Hawkins, Drake, and other discoverers in this country, involving long ocean journeys, directed attention to the necessity for some more accurate information being afforded to the science of navigation.

The navigators of three hundred years ago depended almost entirely on "dead reckoning," or the estimated course and distance run by a ship, assisted by observations of the sun and stars made with instruments of the simplest description. The only charts in use represented the world as a flat surface, the meridians being shown as parallel straight lines as far apart in all latitudes as they are at the equator, and the degrees of latitude being made everywhere equal to one another, and also to the degrees of longitude. In 1569, Mercator drew a chart of the world on which the meridians were still represented by equidistant and parallel straight lines; but the degrees of latitude were increased in length on receding from the equator, in the same proportion that the distances between the meridians on the globe were extended. The principle on which Mercator's chart was drawn was explained in a book entitled "The Errors of Navigation," by Edward Wright, and published in this country in 1599. Since the publication of this work all sea-charts have been drawn on this projection, which has the advantage of showing a ship's actual track as a straight line.

An instrument for ascertaining a ship's speed was invented in 1577, consisting of a small log of wood attached to a line. This was thrown overboard, and the time taken to run out a certain length was measured by the repetition of a sentence. The measurement obtained by repeating these words was subsequently superseded by the use of minute-glasses divided into two compartments, one of which contained sand, which occupied

a definite time in running from one division to the other, a practice which is continued to the present day as a check on other instruments. The speed of a vessel now is generally ascertained by a self-recording log.

The only instrument in use in the middle of the sixteenth century for taking the altitude of the sun was the "forestaff," which consisted simply of a wooden rod three feet long and an inch square, with another rod, called the transversal, attached to it in the centre at right angles, and which could slide backwards and forwards. The observer placed his eye at one end of the rod, and moved the transversal along it until he could see the two objects to which it was directed through two holes at the end. The angle subtended by the two ends of the transversal at the different distances from the eye was marked on the rod. The astrolabe and the backstaff were instruments of a similar character, and were in use until the sextant was invented in the middle of the eighteenth century.

A list of the nautical instruments used in the strange and dangerous voyage of Thomas James in the years 1631–32, to discover the north-west passage through the Arctic Sea, included a quadrant of old seasoned pear-tree wood divided with diagonals even to minutes, four feet in semidiameter; an equilateral triangle of light wood, whose radius was five feet; a wooden quadrant of two feet semidiameter; and four staves for taking altitudes and distances in the heavens.

In 1614, the system of working a ship's course by trigonometry was introduced by Handson, and a few years later Gunter brought out his scales and sector.

In 1675 the office of Astronomer Royal was created, and observations were systematically commenced which have since enabled this department to place at the disposal of mariners the complete and reliable information with which every navigating officer is furnished.

J. Flamstead was appointed the first Astronomer Royal. The sum of £520 was all that was expended in the establishment of the royal observatory. Flamstead's salary was £100 a year, out of which he had to purchase his instruments, and in return for which he had, in addition to his duties as astronomer, to teach two of the boys at Christ's Hospital navigation. He commenced his observations with an iron sextant of seven feet radius and a quadrant of three feet radius, two small telescopes, and two clocks.

The observations and information collected by Flamstead and his successors led to the publication of a number of tables for the use of navigators by Maskeleyne, the Astronomer Royal in 1767, and also to the issue of the "Nautical Almanac." This publication contains tables giving the position of the moon with reference to the fixed stars for every third hour throughout the year, the position of the various planets, and the eclipses and occultations of Jupiter and his satellites, and many similar tables required by mariners. It is published by direction of the Admiralty four years in advance, and as a proof of its use to mariners, it may be stated that between fifteen and sixteen thousand copies are annually disposed of.

In 1714, the British Government offered a reward for the discovery of a means of accurately determining longitude at sea; £20,000 was to be given for any method giving a result within thirty miles of the truth, as tested on a voyage between this country and the West Indies, and £10,000 if within sixty miles. Twenty-one years afterwards Harrison, a watch-maker, received £500 as a reward for the construction of a chronometer; and later on £5000 for an improvement on his first invention; and the whole reward was paid him in 1773.

In the sixteenth century there were no reliable maps or charts. The only charts in use were called "Waggoners," from the Dutch hydrographer, Wagenhair, who produced several small charts about the year 1584. In 1588 his "Speculum Nauticum," a book of sailing directions, was translated into English. In 1671 a book of sailing directions, called "The English Pilot," was issued by John Sellers. It was a collection of sketches of the coasts of this country, of the North Sea, and of France and Spain, accompanied by sailing directions. In 1795 the office of Hydrographer was established at the Admiralty, and Alexander Dalrymple appointed. Captain Hurd, his successor, may be said to have originated the "Charts of the Coasts and Harbours in all Parts of the World," which are now issued by the Hydrographic Department of the Admiralty at a very small cost.

In the same department are also prepared the various volumes of Sailing Directions, giving particulars of the nature of the coast, the set of the tides, the depth of water, and other particulars of the coasts and harbours frequented by British ships. The various charts issued by the department at the present time number upwards of three thousand, and over a hundred and

sixty thousand are issued in a year. The Sailing Directions extend to fifty volumes, in addition to supplements which are constantly being issued. The cost of the department is nearly £50,000 a year, exclusive of the cost of about seven ships of the royal navy engaged in surveying.

Standard Datum.—The advantage to hydrographic surveying of having a common standard or datum to which all observations can be referred is obvious.

In 1860, the French Government issued an order fixing the datum of all levels for France on the mean level of the Mediterranean Sea at Marseilles. This is known as the zero of Bourdaloue, and is used on all plans for public works and for military purposes. The general survey of France, carried on since 1884, was connected with the Italian, Austrian, Dutch, and German systems, which embraced points on the coasts of the Mediterranean, Atlantic, North Sea, and Baltic and enabled the mean level of these seas to be compared, and the discrepancies which previously existed to be corrected. It was found that practically the level of these seas is the same.

In 1783, under the advice of M. Cassini, the French and English Governments directed that a series of triangles should be carried from London to Dover, and thence connected by observations across the English Channel with the triangulation already executed in France, so as to ascertain accurately the relative situation of the Paris and Greenwich observatories. In order to carry out this survey, a base-line five miles long was measured on Hounslow Heath in 1784. This was remeasured in 1791, and formed the base-line on which the trigonometrical survey of this country was founded.

The datum for the level of the ordnance survey adopted by the English Government is the mean level of the sea at Liverpool, which coincides with small variations with the level all round the coast. It was also assumed by the committee of the British Association that the mean level of the sea on the south side of the English Channel is the same as on the coast of this country. The datum used by the Admiralty for their charts is the mean level of low water of spring tides at the different parts of the coast. In the Appendix will be found a table in which the local data and gauges of all the principal ports of this country, and also the foreign data, are reduced to the common standard of the English ordnance datum. The countries which have adopted

the mean level of the sea as their datum are as follows: Belgium, the mean level at Ostend; Spain, at Alicante; Portugal, at Cascaés; Russia, the Gulf of Finland; Holland has taken the level of high water at Amsterdam, or 0·14 metre (·459 feet) above mean level; Germany, a point 0·37 below a mark on the Observatory at Berlin, which is about ·06 feet above the mean level of the Baltic at Swinemunde; Italy, the mean level of the Mediterranean at Genoa; Austria and Hungary, the mean level of the Adriatic at Trieste. The variations of the mean level of the different seas from the Mediterranean as found from the French survey is given in the table in the Appendix.

Hydraulic Literature.—The knowledge of hydraulics, both theoretically and practically, has been greatly aided in its development by the societies which have been established in this country for the promotion of science. The contributions by members of the Royal Society on the tides and other subjects have already been referred to. The British Association, which commenced its meetings in 1832, has also, by the appointment of committees to investigate such subjects as the tides, the theory of waves, and other similar subjects, and by placing funds at their disposal for the purpose, has enabled work to be done and different subjects investigated which in other countries are only undertaken by the direction and at the cost of the Government.

In 1818 the Institution of Civil Engineers was established, and incorporated by royal charter in 1828, the first president being Thomas Tellford. The *Proceedings* of this institution contain most valuable records of papers contributed and discussions held thereon on all subjects connected with hydraulic science from which materials have been very largely drawn in the preparation of this book. Similar institutions of engineers have been established in Ireland and in Holland and America, and the *Transactions* of these societies contain many valuable papers on hydrology. In France the whole of the works for the use of the navigation, both on the Coast and in the interior, are under the care of the Government. A special department, called "The Ponts et Chaussées," with a large staff of specially trained engineers, has the charge and maintenance of the harbours, rivers, and canals, and all new works are designed and carried out by the Government engineers. In Holland, although many large hydraulic works have been carried out by private enterprise, the

care generally of the rivers and navigation works is undertaken by the Government, a special department, termed "The Water-staat," with a large staff of engineers, being maintained for the purpose. In Belgium, Germany, and Russia the navigable rivers and harbour works are under departmental control. In America the funds for the improvement of the large navigable rivers and harbours of the country have been paid for by votes appropriated out of the national funds, and in the majority of cases have been carried out by the State engineers. There is not, however, in the United States a special department, the work being done by the engineers attached to the army.

The meetings of the International Congress on navigation which have, within the last few years, been held at Brussels, Vienna, Frankfort, Manchester, and the last at Paris in 1892, have been the means of disseminating a very large amount of information as to the practice of hydraulic engineering in the different countries of the world, more especially with reference to interior navigation. The papers on the practice, theory, and economics of engineering and navigation afford a wide range of information on these subjects.

In 1803, J. Phillips, who had been employed by Brindley in the construction of the early canals, published a "General History of Inland Navigation, Foreign and Domestic." In 1831, J. Priestley also published an "Historical Account of the Navigable Rivers and Canals of Great Britain," with a large map in six sheets. Both these works deal chiefly with inland navigation, and afford very little information as to tidal rivers.

The development of hydraulic science has also been largely aided by books contributed by engineers. In 1841 a treatise on the "Improvement of the Navigation of Tidal Rivers" was published by W. A. Brookes, the engineer of the river Tyne. The greater part of this work is devoted to the examination of the cause of bars in rivers, and of the course to be adopted for obtaining an improvement of the depth over bars. Mr. Brookes's theory is that bars are due to the flood-tide being checked by the back water, and, being of greater specific gravity, endeavouring to force its way up under the outflowing ebb like a wedge; being unable to do this, it merely elevates the lighter effluent water, and this, being checked by the opposition of the tidal water, yields to the latter the sand and other materials in suspension. The remedy for this, he suggests, is by increasing

the tidal wave and effecting the rapid discharge of the back water. He also controverts the contention of Frisi as to the best position for groynes for directing the current of a river, and advises that these should be placed at right angles to the stream, on the ground that the eddy produced at the back of a groyne placed in this position prevents damage from bodies floating down the stream, which are drawn into the eddy and settle there. These and the deposit of the matter brought in suspension in the water speedily fill up the space between the end of the groyne and the shore. Mr. Brookes also contended that in training a tidal river there is an advantage in giving a preponderating direction of the stream to one side of the channel by rendering it slightly concave. By this means he contends that a greater depth will be maintained in the channel at low water than in a straight channel; that, in training work carried out in sandy estuaries, a single concave training wall will be frequently found sufficient to maintain the channel in one course; and that piers at the mouths of rivers should always effect their junction with the sea by a concave pier on the windward side, by which means the outer division or convex side of the pier would shelter the interior of the channel from the prevailing gales, and prevent the range of the waves running along the face of the pier. He considers that a curve having a radius of three miles will ensure a more easy navigation than is found in channels having straight reaches.

In the year 1844 a Royal Commission was appointed to inquire into the condition of the harbours of this country. Every port of consequence in Great Britain was inspected, and local inquiries held. The attention and inquiries of the commissioners seem to have been principally directed to the necessity of having a controlling authority over harbours and tidal rivers; and to the damage which had been done by landowners and others by enclosing spaces covered by tidal waters, thus diminishing the quantity of tidal scour, and deteriorating the outfall. The inquiry extended over the years 1845–7, and the report and evidence collected, with plans of several of the ports, were published in four volumes.

In 1853, Captain Calver, who was employed for several years in the hydrographic department of the navy, and in the course of his duties was engaged upon surveys of most of the estuaries and ports in this country, published his valuable

treatise on "The Conservation and Improvement of Tidal Rivers," and supplied the first code for guidance in the management of tidal channels which had been published. Captain Calver contends that every portion of the tidal expanse of a river has a value peculiar to itself, and that reductions of the tidal capacity must lead to a deterioration of the channel, the fresh water alone being powerless to maintain a sea outlet; that the supply of material which encumbers a river comes from the interior, and not from the sea; that the improvement of the tidal propagation is a test of the improvement of the tidal compartment of a river. These and the other matters dealt with by Captain Calver will be referred to more fully in a future chapter. Captain Calver devotes one chapter of his book to bars and the theories which have been put forward to account for their formation, and points out that it is a hopeless task to attempt to get rid of bars in tidal rivers by projecting piers or other works solely with a view of reaching beyond the region of movable matter, as the collection of matter about such a projection is merely a matter of time; and that the true direction of improvement is by establishing the preponderance of the inner scouring power as the superior one, and that piers should be designed with a view to achieve this end.

In 1845 a work on tidal rivers, containing descriptions of the principal tidal rivers in France and the means adopted for their improvement, was published in Paris by M. Bouncicau; and in 1861 a work on the action of the tides in rivers by M. Partiot.

The work on "River Engineering," published by Mr. David Stevenson in 1858, and on "Harbours," by Mr. Thomas Stevenson, were both founded on articles which had previously appeared in the "Encyclopædia Brittannica." Mr. Stevenson's work on "River Engineering" was the result of a very extended range of practical information acquired by him from surveys and works carried out under the direction of his firm on many of the principal rivers of this country, and may be considered as the standard work on the subject. His book deals generally with the laws relating to the motion of water, and the principles to be observed in carrying out works for the improvement and maintenance of rivers and channels; but its principal value is the record of facts observed and the description of works carried out. With regard to tidal rivers, he generally endorses the

doctrines laid down by Captain Calver, and thus summarizes the objects to be sought and the beneficial effects to be obtained from works of improvement when carried out on correct principles: To deepen the level of the low-water line. To increase the range of the tide. To accelerate the propagation of the tide through the channel of the river. To prolong the duration of the tide in the river. To equalize the velocity of the tidal currents, removing rapids and bores. To add to the beneficial scouring power of the river, and to increase the navigable depth.

Mr. Thomas Stevenson's work on "Harbours" is a practical manual on the construction of works designed to resist the action of the sea and waves, and contains a large amount of information as to the power of the water on works of defence and other matters, derived from a wide experience in designing and carrying out piers and harbours and lighthouses.

Mr. Vernon Harcourt's book on "Rivers and Canals," published in 1882, and his "Harbours and Docks," in 1885, describe the physical characteristics of some of the principal navigable rivers, and of the works which have been carried out for their improvement, and for providing accommodation for navigation. These works afford valuable information to the hydraulic engineer engaged in practical work.

In 1884 Sir Charles Hartley delivered a lecture before the Institution of Civil Engineers, being one of a series on Hydronamics, on the "Inland Navigation of Europe," in which will be found a full account of the works carried out for the improvement of the Danube, and a description also of the condition of the principal navigable rivers of Europe. The Danube works will also be found further described in papers by the same author in the Minutes of Proceedings of the Institution of Civil Engineers.

In 1881 Mr. J. T. Mann published a treatise on the cause of formation and treatment of bars. Mr. Mann, from experience gained in connection with the works for the improvement of the bar of the Liffey in Dublin harbour, considers that the most effectual way of dispersing, and preventing the re-formation of bars is by what he terms "induced tidal scour," or the concentration a large body of tidal water on the particular part of the channel which requires deepening.

A very valuable addition was made to hydraulic literature by the publication in 1851 of the "Manual of Hydrology," by

N. Beardmore. The author of this work, during a long career as engineer engaged in river work, had collected together a great mass of facts and statistics relating to hydraulic engineering, and as to tides and the physical conditions of rivers. In his "Manual of Hydrology" he has given many of these, together with a large number of tables, for calculating discharges and for other purposes. This book still remains the standard handbook of the hydraulic engineer.

The works of Downing and Neville, published about thirty years ago, made a considerable addition to the knowledge of theoretical engineering. More recently works have been published by Merriman and Flynn on the same subject in America.

Downing, in his "Elements of Practical Hydraulics," gives a simple adaptation of the formula of Chezy for ascertaining the velocity of water in rivers and open channels which has the merit of simplicity, requiring few figures in its working. By this formula the velocity found is the product of the square root of the hydraulic mean depth multiplied by twice the fall per mile, reduced by a constant depending on the character of the stream: $V = \sqrt{R \times 2F} \times C$. Neville's book of "Hydraulic Tables and Coefficients" contains, besides the tables, a considerable amount of information, derived chiefly from experience gained in the works carried out for the improvement of the rivers and drainage of Ireland.

In 1870 Herr Kutter and M. Ganguillet made a series of experiments on watercourses in Switzerland, with the object of deducing a more exact law for the effect of roughness and declivity on the discharge, and, as the result of their observations, produced a formula sufficiently variable to be adapted to rivers and channels of varying character. Kutter's "Hydraulic Tables," translated by L. D. A. Jackson, was published in this country in 1876. The formula is complicated, and, the observations having been made on rivers having steep inclinations and high velocities, the coefficients do not give any more exact results when applied to tidal rivers than can be obtained with a formula of more simple character.

About the year 1880 a series of velocity observations was made by Major Allan Cunningham on the canals in India for the Government, and also with the object of settling a formula for obtaining the velocity in canals and irrigation channels.

In 1861 the Government of the United States voted funds

for an investigation of the conditions attaching to the river Mississippi, with a view to obtaining correct information as to the cause and means of preventing floods and the constant changes in the course of the river. The result of this survey was given in a report by Humphreys and Abbot, published in 1861. Beyond the knowledge to be derived from a study of the facts recorded, this work has not added much to what was previously known, except perhaps as to the mean velocity of water flowing in a large river.

Messrs. Humphreys and Abbot having conducted a large number of experiments, and compared the results with those obtained with the existing formulæ, found that none of those having a fixed coefficient agreed with their researches, and that the coefficients, when variable, extended over a very wide range. They therefore produced a new formula, in which, in place of the hydraulic mean radius, a new term, called the prime radius, was adopted, being the breadth of the surface added to the product of the area divided by the perimeter. The fourth root of the inclination was also taken instead of the square root. Their formula will be found in the Appendix.

In 1873 a similar investigation was made, at the instance of the Argentine Confederation, of the rivers Parana, Uruguay, and La Plata, by J. J. Revy, the results being given in the work on "Hydraulics in Great Rivers." A great deal of valuable information will be found in this book as to the flow and discharge of water in large rivers having a very small surface inclination, and as to the effect of the tides at great distances from the sea. Information is also afforded as to the method of surveying rivers of this character, and the use of floats and current-metres for ascertaining the velocity.

CHAPTER II.

HISTORICAL ACCOUNT OF WORKS CARRIED OUT FOR THE IMPROVEMENT OF TIDAL RIVERS AND NAVIGATION.

ALTHOUGH the science of hydraulics has been reduced to exact laws within modern times, very extensive hydraulic works were carried out by the ancients. These were principally in connection with inland navigation, water-supply, and the drainage and reclamation of land.

It is a remarkable circumstance that, considering the large extent of the land compared to the population that existed in the early days of the world, such labour and cost should have been expended in draining and embanking lands which otherwise would have been uninhabitable. A very considerable tract of land was made habitable by drainage by the Romans in Italy. The greater part of Holland exists only by the aid of artificial works, and was reclaimed from the sea by the skill of the early engineers. In this country a very extensive tract of land on the east coast was enclosed from the sea by embankments extending for several miles along the coast and up the rivers. In modern times some of the principal settlements in America are along the course of the Mississippi, the water of which river is with difficulty restrained from inundating the reclaimed lands by massive embankments.

The earliest navigators of whom we have any record were the Phœnicians, and their principal city, Tyre, was built on a series of islands which ran parallel with the shore of the main land, and thus formed a natural breakwater. These islands were united in the time of King Hiram by filling up the space between them. The area of the island was also enlarged by filling up the sea with stone and earth brought from the mainland. The Phœnicians possessed a large fleet of boats, in which, as early

as the thirteenth century before the Christian era, they navigated the Mediterranean, and their merchantmen traversed unexplored countries, freighting their vessels with their own wares and those of Egypt and Assyria. Their vessels passed through the Straits of Gibraltar, and colonies were established in Spain and the Scilly Islands; they also came to this country to fetch supplies of tin and lead for importation into Greece and Asia, leaving in exchange pottery, salt, and cloth. For the protection of their vessels the Tyrians constructed two harbours. That on the north had piers of stone carried out from the shore about 700 feet into the sea, leaving an opening of 100 feet, and enclosing a space of about fifteen acres. The harbour was thus made secure from the effect of the north wind. A breakwater and harbour was also constructed on the south of the island rather more capacious than that on the north, the two being connected together by a canal excavated through the middle of the city (see Fig. 1).

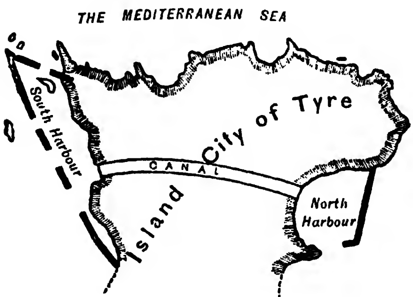

FIG. 1.—Harbour of Tyre.

In ancient Egypt very considerable works were carried out in the construction of canals for facilitating the navigation of the interior and for irrigation. A canal was made for the purpose of effecting a junction between the Nile and the Red Sea, thus opening up a communication for vessels coming from the East by the Red Sea to the Nile and the Mediterranean, and so to Greece and Rome. Another large hydraulic work was the conversion of the large depression in the Fayoum country on the east side of the Nile into the famous lake Mœris, which had a circumference of four hundred and fifty miles. This lake was constructed for irrigation, and was supplied by the canal known as the Bahr Josuf, its name lending credence to the tradition that it was cut in the time of the Pharaohs, under the direction of Joseph. It leaves the Nile at Assiout, and, running for two hundred and fifty miles nearly parallel with it, but at a less inclination, gradually assumes a higher elevation, and, after entering the Fayoum through a narrow pass, discharged its water into the lake. A strong testimony in favour of the skill

with which this work was designed is given by the fact that one of the most prominent and feasible schemes now occupying the attention of the Egyptian authorities for improving the irrigation of Egypt is the plan of Mr. Cope Whitehouse for restoring the area occupied by the site of Lake Mœris to its original purpose.

The great canal of China is supposed to have been constructed at a very early date in the world's history. It runs from north to south of the empire, extending from Canton on the south to Pekin on the north, a distance of 825 miles, along which vessels of one hundred tons were able to navigate. Its breadth is 50 feet, and depth 9 feet. In addition to the Grand Canal, the country has been intersected in every direction by smaller waterways, which are used for the purposes of navigation and irrigation.

Both the Greeks and Romans constructed harbours for the protection of their vessels, which traded with the Egyptian, Phœnician, and other ports. Remains of the ancient Greek piers are to be found at the present time. The Romans carried out considerable harbour works at Ancona, Civita Vecchia, and Ostia. At the latter place two long walls were run out in the time of the Emperor Trajan, and the entrance protected by a stone breakwater, enclosing an area of about one hundred and forty acres, in which there was a depth of 18 feet. A lighthouse 200 feet high was erected at the outer end of the pier. In the harbour there were also one and a half mile of quays, and large warehouses for storing grain. The Romans also carried out extensive works for regulating the Tiber, and for draining and reclaiming marsh lands in Italy and the countries which they conquered. In this country, in addition to the embankments which they constructed for reclaiming the Fenland, they also cut the canal known as the Fosdyke running from Lincoln to the Trent, and the Cardyke running from Lincoln to the river Nene. The former, eleven miles in length, is still in use as a navigation; and the latter, forty miles long, is partially used as a means of drainage. After the time of the Romans, a long interval appears to have elapsed before there is any record of attention being paid to works of navigation or drainage.

About the end of the fourteenth century Leonardo da Vinci first made use of the principle of the lock in the canal called the

Naviglio Grande, from the Ticino to Milan. The invention of the lock as a means of overcoming the variations in level, and in obtaining a regular depth of water, gave considerable impulse to the extension of inland navigation. The first application of locks in this country was by John Trew on the Exeter Canal in 1566.

In 1666 Pierre Paul Riquet commenced the works on the famous Canal-du-Midi, or, as it is generally called, the Grand Canal of Languedoc. This canal crosses the isthmus which connects France and Spain, and extends from the river Garonne at Toulouse to Cette on the Mediterranean, thus providing a waterway from the Mediterranean to the Atlantic. The length of the navigation is 158 miles. It rises 207 feet, and has a hundred locks, passes over several rivers, and in one place is carried by a tunnel through the mountains. It terminates in a harbour and a sea entrance at Cette. The cost of this canal was £1,320,000. In addition to the numerous engineering difficulties which Riquet successfully overcame, he was continually embarrassed by the want of funds. Considering the boldness of the undertaking, the number of constructional works required, and the want of previous experience, this must be regarded as a work which reflected immense credit on Riquet as an hydraulic engineer.

The Early Engineers.—In 1478 Bishop Morton made a commencement in the improvement of the rivers draining through the fen country in the east of England, by making a new channel for the river Nene from Peterborough to Guyhirn. It was not, however, till the middle of the seventeenth century that the work was continued, when a large amount of money was expended by adventurers in attempts to reclaim the fen.

There had been so little work for hydraulic engineers in England that it became necessary, when such services were required in this country, to obtain them from other countries, and generally from Holland. The engineer whose name has left the most enduring record behind him was Cornelius Vermuyden, a Dutchman, who was brought over from Holland in 1621 to stop a breach which had occurred in the banks of the Thames. He was afterwards employed in the drainage of Hatfield Chase, which he accomplished by carrying the water direct to the Trent by the river Idle; embanking the river Don, and providing a new outfall for it by a cutting called the

Dutch River, which joins the Ouse near Goole, and is both tidal and navigable for barges. Subsequently he was employed on the great level of the fens.

Westerdyke, another Dutch engineer, was also called to advise on the works to be carried out.

Vermuyden and Westerdyke held different views as to the principles on which the works of improvement should be carried out. Westerdyke contended for the views originally taught by Guglielmini, that the water should all be concentrated in one main channel; that the first consideration should be the improvement of the outfall and the trunk rivers, and the free run of the tides up those rivers. Vermuyden, on the other hand, advised the separation of the drainage water from the tidal, and the carrying of this by long straight cuts, often running nearly parallel with the rivers. Thus the old Bedford River, 21 miles long and 70 feet wide, was cut, extending from Erith to Denver, and, running nearly parallel with the Ouse, with the object of relieving and taking off the floods in that river. Other large main drains were also made, diverting the water from the upper part of the Ouse and discharging it lower down, by which means an outfall for the lowlands was obtained, which hitherto had been more or less under water. These drains were protected by self-acting doors where they joined the tidal river, which allowed the drainage to flow out at low water, and prevented the tides from flowing up the drains. Vermuyden's plan lent itself more readily to the circumstances of the case than Westerdyke's, as the latter required the united action of all the parties interested, whereas Vermuyden's system could be carried out piecemeal, each district effecting its own drainage independent of the others. The latter system prevailed in all the early works of drainage. As a general system it proved a failure, and works had to be subsequently carried out for deepening and straightening the main rivers, and, by concentrating the flow of the water, maintaining the channels by scour to their outfalls. The fact that it was found necessary to lift the water out of Vermuyden's drains by wheels driven by wind-power, and afterwards by steam, testified to the failure of the system.

Had Westerdyke's advice been followed, the expenditure of large sums of money and the waste of a large area of land by the making of unnecessary drains would have been saved. Even if the conservation of the main river had not provided a

sufficiently low outfall for the discharge of the water off the low lands by gravitation, it could have been pumped direct into the river, instead of first having to traverse a long length of unnecessary drain. This fact has since been realized, and the improvement of the outfalls tardily carried out, showing the correctness of the principles of the early engineers as to the advantage of the scour derived from a concentration of water.

The fen country may be considered the nursery of modern river-engineering. All the early English engineers were engaged in or consulted as to the works carried out for the improvement of the tidal rivers as bearing on the reclamation of the Fen-land. Following at a considerable interval after Vermuyden, the adventurers sought the advice and assistance of Captain Perry, who had successfully accomplished the stopping of the great breach in the banks of the Thames at Dagenham, and was also extensively employed in carrying out navigation works in Russia.

After Perry came Nathaniel Kinderley who first advised and prepared the design for straightening the river Ouse by the Eau Brink Cut above Lynn, which was afterwards carried out under the direction of Rennie, effecting a depression in the low-water line of the river of not less than 8 feet, an enormous advantage to the drainage of a large tract of low fen-land. He also improved the Nene by a new cut below Wisbech. Kinderley was also engaged in carrying out the new channel of the river Dee from Chester to Flint, and the works pertaining to the reclamation of the large area of land which became the property of the Dee Reclamation Company. Other names of engineers engaged on the fen rivers were Elstob, Grundy, Chapman, Langley Edwards, Golborne, Thomas Telford, Smeaton, Huddart, John Rennie, and James Walker. While some of these are forgotten, the names of others are still familiar, and will always be remembered by the works which they carried out in other parts of the country, and which remain as enduring monuments of their skill. Langley Edwards was the engineer to whose hands was committed the carrying out of the works necessary for making a new cut for the river Witham above Boston, and for the improvement of the drainage, and also for rendering the river navigable. This scheme involved the construction of the structure known as the Grand Sluice, by

means of which the tidal water is excluded from the river at a point about eight miles from the estuary. The policy of thus stopping the free run of the tide was the subject of much controversy at the time, and was condemned by Elstob, Chapman, Telford, and Rennie, and more recently by Sir John Hawkshaw. Smeaton, however, who was engaged in reporting on the Witham about the time when this sluice was erected, appears to have approved of the principle, and afterwards advised a similar treatment for the Clyde.

The name which stands out most prominently amongst the engineers engaged on the fen rivers is that of John Rennie. The works which he carried out for the drainage of the Lincolnshire fens, and for Hatfield Chase and the Isle of Axholm, and the substantial stone sluices and bridges which he constructed at the outfall of his drains, remain as enduring monuments of his skill. The principle on which Rennie acted in these works was first to provide for the high-land water by cuts discharging into the river, and to carry the low-land drainage water by independent channels. He always advised the maintenance and integrity of the trunk rivers, and designed his works accordingly, although in some instances his advice was overruled, and he had to submit to the wishes of his employers. These works of fen drainage were sufficient to have formed the reputation of any engineer, but were only a very small part of the work of Rennie. There is hardly a tidal river or harbour in the kingdom whose records do not contain reports made by him, and in most of which will be found breakwaters, piers, docks, or works of river improvement which were carried out by him.

Inland Navigation.—In the early days of the history of the navigation of this country ships were principally engaged in the commerce existing between England and Flanders, Normandy, and the country along the Rhine. The nearest and most convenient port for these vessels was the estuary of the Wash on the East coast, and, apart from London, the two Wash ports, Boston and Lynn, had a larger amount of shipping than any other places. The merchandise brought to these ports was carried for a considerable distance into the interior by means of the Ouse, the Witham, and the other fen rivers.

Down to the middle of the last century the foreign trade and

commerce of this country was comparatively insignificant. This was in a great measure due to the want of means of interior communication. While France, Holland, Russia, and Italy had been developing their inland waterways, and thus opening up means of communication, in this country merchandise brought from abroad had to be conveyed into the interior of the country by pack-horses. Although provided with good natural harbours on the coast, and with tidal rivers running up into the country, scarcely anything had been done up to the seventeenth century to take advantage of these natural waterways and to extend navigation inland, either by improving the rivers or by means of canals. In a work entitled, "England's Improvement by Sea and Land," published in 1677, one Andrew Yarranton called attention to what had been done by the Dutch to facilitate navigation, and urged that England should follow their example. He contended that England possessed great natural advantages in having large rivers well situated for trade, with plenty of material, such as wood, iron, coal, tin, lead, wool, and other products to trade with, but that these could not be used to advantage without means of transport. He proposed that the upper part of the Thames should be improved and connected with the Severn and the Avon. When this was done, material could be transported from Bristol, Staffordshire, Cheshire, and Wales, to London.

The opening up of trade with India, after the establishment of the East India Company, led to a considerable increase, not only in the number, but size, of the ships employed, which received a still further development as the colonies established in America grew in number and importance.

There can, however, be no question that England could never have attained the pre-eminence she now holds as a trading country but for the facilities afforded for the transport of merchandise by the system of water-carriage due to the construction of canals. The opening of the Bridgwater Canals about 1761 not only reduced the cost of the conveyance of minerals and merchandise to one-fourth what it had previously been, but also provided a means of transporting them in large quantities. The greatly increased number of ships required to accommodate the traffic brought to Liverpool by the new canals raised it to a first-class port. Following on the opening of these canals, the tonnage of English ships increased threefold. As

Liverpool and Manchester owe their rise to the Duke of Bridgwater's canals, so Leeds may ascribe its prosperity to the Aire and Calder system. Birmingham would never have developed its hardware trade but for canals connecting it with Liverpool and the seaports. The potteries and the salt districts were developed by the Grand Junction Canal and the canalized river Weaver. London could not have retained its position as the chief port of the kingdom but for the canals which distributed the produce brought from foreign ports, and conveyed the goods exported from the interior by the system which placed its river and docks in communication with all parts of the country.

James Brindley, to whose great perseverance, genius, and skill was due the carrying out of the system of canals for connecting the Duke of Bridgwater's collieries with Manchester and also with Liverpool, and the subsequent canal system which extended all over the country, was a self-taught engineer, and a thorough example of the type of what all our great engineers have been. Having a true mechanical genius and a capacity of adapting the resources at his command to the results he had to accomplish; not relying on what had been done before, but originating new plans of his own; thoroughly self-reliant, honest, and hard-working, with a dogged determination never to be beaten;—he succeeded in carrying out his schemes in spite of all obstacles, and in his works left behind him examples of bridges, locks, aqueducts, and tunnels which have been taken as models by subsequent engineers, and many of which works still remain as enduring monuments to Brindley's skill as an hydraulic engineer.

Foreign Engineering.—Although after Brindley's time we no longer looked to Holland for assistance in our hydraulic works, yet the Dutch still retained their reputation for the grand engineering works which have been carried out for the improvement of her waterways. Holland itself is a standing example of the power of rivers to transport material, the whole of the country consisting of alluvial matter brought from other parts of Europe by the Rhine, the Maas, and the Scheldt, and deposited at their outfalls on the coast of the North Sea; and of the enterprise of the people and the skill of the engineer in wresting from the sea the most valuable tract of fertile land in Europe. The drainage works, for their extent, are unparalleled in any other

part of the world, the principal main drains consisting of large canals which afford communication throughout the country, and, by means of the large rivers which intersect Holland, over a large part of Europe. The enterprise which first prompted the inhabitants of these low countries to embank and reclaim them, and to carry out extensive works of hydraulic engineering, has continued up to the present time. The land lying below the level of high water at sea was formerly drained by innumerable windmills, which, with the aid of large wooden scoop wheels, lifted the water out of the polders into the sea. The Dutch were amongst the first to apply steam-power to this purpose. For the drainage of Lake Haarlem, covering about 42,000 acres, and involving the construction of over a hundred miles of canals and main drains, about fifty years ago three sets of large steam pumping-engines, placed at different parts of the lake, were employed, being the largest pumping-engines constructed up to that time. These were designed and erected by Messrs. Gibbs and Deane of Cornwall, and each consisted of eleven pumps 63 inches in diameter placed concentrically, and worked by a beam engine actuated from a steam-cylinder 12 feet in diameter, and together capable of lifting 660 tons of water a minute 16½ feet high. The reclamation of this polder cost £781,500.*

At the beginning of the present century, in order to facilitate the navigation to Amsterdam, a ship canal was constructed from the North Sea to that port. The North Holland Canal, which has been described as "the greatest work of its kind in Holland, and probably in the world," was commenced in 1819 and completed in 1825. It is 50½ miles long, is 30 feet wide at the bottom, and has a depth of 18½ feet, and cost about a million of money.

This canal has since been practically superseded by the Amsterdam Ship Canal, which has shortened the distance 36½ miles. This canal, commenced in 1865 and finished in 1876, was carried out under the direction of Herr J. Dircks, who prepared the original designs, and of Sir John Hawkshaw, as consulting engineer. It is 15½ miles long, 88 feet wide at the bottom, and has 23 feet of water. It is approached from the North Sea through two piers two miles in length, which form an outer harbour of 250 acres, and protects the two entrance locks,

* A full description of this work will be found in "The Drainage of Fens and Lowlands," by W. H. Wheeler.

which are respectively 390 feet long by 60 feet wide, and 227 feet by 40 feet. The works involved the construction of several embankments, including one across the Zuyder Zee, and the reclamation of a large tract of land. The total cost was about three millions of pounds.

In order to improve the navigation up to Rotterdam, an entirely new outfall has been made for one of the principal rivers of the country, and its channel throughout regulated and deepened. The works on the Maas were commenced in 1863, and completed in 1871, under the direction of Mr. P. Caland, the engineer who originally designed them. The total cost of these works has been £2,840,000.

The other most noticeable works in connection with the improvement of the rivers of Europe for the purposes of navigation were those of the Seine, from the estuary to Rouen, which were commenced in 1846, and carried out from the designs of M. Bouncieau at a cost of £1,198,000; the opening up of the Danube to the navigation of large steamers, by deepening and improving the Sulina branch and removing shoals and bends in the river, under the direction of a European commission. These works were carried out from the plans of Sir Charles Hartley, and under his direction. The cost of the piers and opening out the passage from the Black Sea to the river was accomplished for the comparatively small sum of £185,352.

The Suez Canal, commenced in 1859 and opened in 1869, shortened the distance to India from this country by about four thousand miles, or nearly half. This canal, 87 miles in length, of which one-fourth is through lakes, was made 72 feet wide at the bottom, and with 26 feet of water. The excavation amounted to a hundred million cubic yards. It was constructed under a concession obtained by M. Ferdinand de Lesseps from the Khedive of Egypt, M. Lavallé being the engineer who carried out the works. The cost when opened was £16,613,000, of which only £11,653,218 was for works. This, however, does not include the value of the forced labour supplied by the Egyptian Government. The construction of this canal was not regarded favourably by this country. It was reported against by Mr. Robert Stephenson, who was sent out to investigate the proposed scheme. Mr. Stephenson's experience, having been almost entirely that of a railway engineer, led him to look unfavourably on the proposed waterway, and to express the opinion that a

railway would be more serviceable. Subsequently England acquired a large interest in the canal by the purchase of the shares held by the Khedive for £4,000,000, and is now its chief supporter, nearly 80 per cent. of the tonnage passing through the canal being British ships. The amount of shipping which passed through the canal the first year after it was opened was 486 vessels, of a net tonnage of 436,609; and in 1890, 3389, of 6,890,000 net tons. The canal has been much improved since it was opened, and is now being widened and made deeper in the shoal places.

In America and Canada very considerable works have been carried out for the improvement of the harbours and tidal rivers, and also in developing the inland waterways, more especially those in connection with the Great Lakes. The most important work in connection with these was the construction of the Welland Canal and the Sault St. Marie or "Soo" Canal and locks, by means of which communication was opened out between the chain of lakes to the St. Lawrence on the one side, and on the other by Lake Erie with the Ohio and the Mississippi; and by Lake Erie and the River Hudson with New York. Vessels of sufficient size to cross the Atlantic can now navigate from Duluth, at the head of Lake Superior, and from Chicago, at the head of Lake Michigan, by the St. Lawrence to this country. The value of this waterway will be further realized when it is considered that Chicago is a thousand miles inland from the nearest seaport on the St. Lawrence. The canal, which is only one mile long, and the lock at Sault St. Marie were commenced in 1852, and opened in 1854. The first lock was 350 feet long by 70 feet wide and 12 feet deep. Between 1870–1883, the lock was increased to 575 feet by 80 feet, with 17 feet depth of water. The traffic increased so rapidly that the lock has recently been again enlarged to 800 feet long, 100 feet wide, with 21 feet on the sill. A new lock and connection is also being made on the Canadian side. The traffic through these locks exceeds that through the Suez Canal, 10,557 vessels, carrying 8,454,435 net tons, having passed through in 1890.

The Mississippi, with its magnificent waterway of sixteen thousand miles, was obstructed at its outfall by shoals or bars, over which there was only a navigable depth of from 8 to 13 feet, thus blocking this river to all except small craft. Through one of these shoals General Eads undertook to open out a

navigable waterway having a depth of 30 feet for a definite sum, to be paid him by the United States Government only on condition that he succeeded in providing the full depth. After very considerable opposition, his offer was finally accepted. He commenced the work in 1875, and four years afterwards had succeeded in accomplishing the given depth, which has since been maintained. His method of operation was by concentrating the scour of the current in one of the passes by two parallel jetties of fascine work, and thus making the water the agent for effecting the improvement of its own course.

Another engineering work of considerable magnitude, for the improvement of the navigation up to New York, was the removal of the rock shoal known as "Hell Gate," so as to give a depth of 30 feet at low water. This was accomplished by first breaking up the rock by submarine blasting, and then removing the *débris* by dredging. This work occupied ten years, and cost altogether over a million of money. The blasting was accomplished by a single explosion, by means of which 270,717 cubic yards of stone were broken up. The waterway to New York was further improved by forming a channel to a depth of 30 feet below low water through the mud and sand of which the estuary which lies between the Atlantic and Long Island is composed, by dredging only, and without any training works, at a cost of £258,550.

Navigation.—The small size of the vessels in which all the foreign trade of this country was formerly carried necessitated very little improvement in the tidal rivers, or accommodation in the ports and harbours beyond that which they naturally afforded. When the foreign trade of this country first began to assume importance, the vessels were scarcely as large as the fishing-smacks of the present day. The craft which then crossed the seas were often not more than twenty or forty tons in size, and in these small vessels voyages were made across the Atlantic and round Cape Horn and into the Pacific. The vessel in which W. Baffin sailed from Gravesend for the discovery of the North-West passage in 1616 was only fifty-five tons, and in this he reached to latitude 77·45°, a height which was not surpassed for the next 236 years. As trade developed, the size of the vessels increased, but so long as wood only was used, the size of the timber necessary for the framing practically prevented the increase beyond a certain limit. It was only after iron, and subsequently steel,

was used for the building of ships that the sizes now in use could be attained. In the early part of the present century, the introduction of steam as a propelling power for ships gave an enormous impetus to navigation and foreign trade, and this, coupled with the use of iron, gave this country the predominance over all others as the ocean carriers of the world.

Steam, as applied to the propulsion of vessels, was first practically brought into use in 1788 by a Scotch engineer, W. Symington, assisted by Henry Bell, the funds being found by Patrick Miller. The steam-vessel then built ran on the Forth and Clyde Canal, and attained a speed of five miles an hour. The *Charlotte Dundas*, constructed in 1801, was used on this canal for many years as a tug-boat. In 1807 Fulton introduced steam-propulsion into America, the engines for the boat having been made in this country by Boulton and Watt. The first seagoing steamer was employed in 1815, in making the voyage between Glasgow and London. The design of the engines used for steam-propulsion was gradually improved and altered, so as to adapt them better for marine work, by H. Bell and David Napier.

In 1825, the merchants of Calcutta offered a premium of a lac of rupees for the first voyage out and home made by a vessel in seventy days each way. The *Enterprise*, of 470 tons, with engines of 120 H.P., made by Maudesley, attempted the voyage, and, although not successful, the venture was sufficient to show that it was quite practicable to propel ships by steam over long distances.

The use of the screw in place of paddles for propelling ships was brought into practical use through the instrumentality of J. P. Smith in 1836, and, after undergoing improvements in design at the hands of George Rennie, became generally adopted.

The first iron ship was registered at Lloyd's in 1837. The same year marked the commencement of the service established by the Peninsular and Oriental Steam Navigation Company. All the earlier vessels of this company were wooden paddle-steamers.

In 1832 the Cunard Company was formed, with a capital of £100,000, for the purpose of running passenger-steamers from this country to America. The first vessel built for the service was the *British Queen*, of 2400 tons, which left London for New York in 1839. The *Sirius*, of 700 tons, had crossed

in the previous year in eighteen days. In 1838 a wooden paddle-steamer, the *Great Western*, of 1340 tons and 750 I.H.P., sailed from Bristol, and reached New York in fifteen days. The *Great Britain*, an iron screw-steamer, was added to the fleet a few years after. The size and speed of the vessels have since continually increased. The *Campania* and *Lucania*, two of the latest additions, being each 12,950 tons, and having an indicated horse-power of 30,000, have performed the journey in a little over five days.

Harbours and Docks.—It is evident that, with such a change in the conditions of the shipping of this country, it became necessary that the tidal rivers and harbours should be altered and improved to meet the growing requirements of the navigation. In the early part of the present century, Smeaton, Telford, Rennie, Walker, Rendel, and others of less note, were actively employed in erecting lighthouses, deepening rivers, building docks, and improving the harbours of the country.

The first wet dock on the Thames was the Great Howland Dock, built in 1660. This has since been absorbed into the system known as the Commercial Docks. The Old Dock, four acres in extent, was built in Liverpool in 1709. In 1802–3. the East and West India Docks on the Thames were opened. The companies who built these docks obtained a clause in their Acts making it compulsory for all ships coming up the Thames with produce from the East or West Indies to discharge their cargoes in them for a period of twenty-one years.

The earliest attempt to improve the tidal rivers in this country for the purposes of navigation may be said to have been made in the Clyde in 1566, when a commencement was made by opening out a sandbank at Dumbuck. It was not, however, until after the middle of the eighteenth century that powers were obtained, and works commenced, under the direction of Golborne, for improving the river from Glasgow to the sea, and which, since continued, have resulted in converting a small tidal river into one of the chief waterways of the kingdom.

The Tyne, from which even as far back as the fourteenth century there is a record of the export of coal, had nothing done for its improvement till the first quarter of the present century, and even up till 1850, when the Tyne Conservancy Act was passed, the works which had been carried out only

enabled vessels of $15\frac{1}{2}$ feet to reach Newcastle. The piers, which have made the river below Shields into a magnificent harbour of refuge, were commenced in 1854 from designs of Mr. James Walker, and have cost the Tyne Conservancy three-quarters of a million of money.

The first works for the improvement of the Tees were commenced in 1808. The works between Middlesborough and the sea, which have converted the Tees into an important navigable river, were commenced soon after the formation of the present commission in 1852. It is unnecessary to refer at any further length to other works of river improvement.

The newest departure of hydraulic engineering is the waterway for connecting Manchester with the sea, designed by and carried out under the direction of Mr. Leader Williams. The Manchester Ship Canal may be regarded as the greatest work of the kind which has yet been accomplished, not so much on account of the amount of money which it has cost, as from the amount of opposition through which it had to struggle into existence, and the engineering difficulties which have had to be overcome. The canal is $35\frac{1}{2}$ miles long; the width at the bottom, 120 feet; and depth of water, 26 feet. The lower fifteen miles is semi-tidal. The docks at Manchester and Salford cover 104 acres, with five miles of quays. The level of water in these docks is $71\frac{1}{2}$ feet above that in the Mersey at Eastham. This difference is overcome by five sets of locks of sufficient size to take the largest merchant vessel afloat. At the entrance from the Mersey at Eastham there are three locks, in size respectively 600 feet by 80 feet, 350 feet by 50 feet, and 150 feet by 30 feet. The other four locks at Latchford, Irlam, Barton, and Modewheel are 600 feet by 65 feet. The canal is crossed by several lines of railway, which have had to be diverted and their level raised so as to give a clear headway of 75 feet under the bridges. The canal is also crossed by a large number of swing bridges, some of which, for carrying the railways across, are very massive, weighing upwards of 700 tons, and having a clear span for one arm of 140 feet. In addition to a large number of roads which had to be carried across the waterway, provision had also to be made for carrying the Bridgwater Canal over on the skew, and this has been done by means of a swing aqueduct; arrangements are also made at the crossing for raising and lowering boats to and from the Ship Canal to the Bridgwater Canal by

means of an hydraulic lift. The excavation required for the canal amounted to over one hundred and fifty million cubic yards, of which ten million was in sandstone rock. The work on the canal was commenced in 1887, and it is expected to be completed in 1894. The cost of the land and works is estimated to amount to ten millions, in addition to which about one million will be absorbed in interest on capital, cost of engineering and management during construction, and expenses in obtaining the Parliamentary powers—which have amounted to about £150,000—and one and three-quarter million paid for the Bridgwater Canal, making a total capital of thirteen millions.

Diving Machinery.—The improvement of harbours and tidal rivers has received great aid by the assistance given, in carrying out the foundation of piers and other submarine works, by the invention of the diving-bell and diving-dress. Several attempts were made from the earliest times to invent a machine to assist divers in remaining under water, but the first really practical diving-bell was that of Edmund Halley, the secretary of the Royal Society, and which is described in the *Philosophical Transactions* of 1717. Improvements were subsequently made on this machine, and it was finally brought to a great state of perfection by Smeaton, who used a cast-iron diving-bell for laying the foundation of the walls of Ramsgate harbour in 1791. Diving-dresses came generally into use at the beginning of the present century, and divers were made great use of by John Rennie and James Walker. The present form of dress owes its efficiency to improvements made by Heinke and A. Siebe, the one having improved the helmet, and the other the dress, about 1829 to 1837. It is unnecessary to enlarge on the value of this invention, and of the great aid it is to the construction of submarine works, in recovering property from wrecks, and in raising sunken vessels. It is sufficient to say that by the aid of the diving-dress a man can descend to a depth of over thirty fathoms, and be able to remain below at this depth for more than half an hour, and at less depths for a considerably longer period.

Lighthouses.—The erection of beacon lights on dangerous parts of the coast has been in practice from the earliest times. So far back as three hundred years before the Christian era there is a record of a "Pharos," or beacon tower, erected for the benefit of sailors at Alexandria, and dedicated to "the Gods,

the saviours of mariners." The earliest record of modern lighthouses is that of Cordouan, at the mouth of the Garonne, which was built of stone 197 feet high, on the top of which was burnt a wood fire.

As shipping increased in importance in this country during the sixteenth and seventeenth centuries, the need for lighthouses and beacons became a matter of urgent importance. The erection of lights at prominent places on the coast, and at the entrance to harbours, was originally undertaken by private persons under charters granted by the Crown. In 1536 Henry VIII. granted one of these charters to a society of merchants interested in the shipping of the Tyne, for the purpose of erecting two light-towers at Shields and Tynemouth. In 1680 a charter of a similar character was granted to the Trinity House of Deptford Strond, giving power to buoy and beacon the Thames and collect dues from vessels, these powers being subsequently extended to the whole of the coast of England; and Lighthouse Boards for Scotland and Ireland were also established.

The first lighthouse erected on the Eddystone rocks, situated about fourteen miles seaward of Plymouth, was constructed of timber by Henry Wynstanley between the years 1696 and 1700. Three years later it was destroyed during a storm, its engineer perishing with it. A second lighthouse, also built of wood, 92 feet high, was erected by John Rudyard during the years 1706–3, and continued to show its light for forty-seven years, when it was destroyed by fire. The lights in the lantern of these houses was supplied from candles. The difficulty of construction on this rock is considerably enhanced by the fact that it was covered with water at every high tide, and, owing to the heavy seas, the work could only be carried on in summer. Rudyard's lighthouse was replaced by the stone lighthouse erected by Smeaton in 1756–59, which, considering the novelty of the work, the difficulties of construction, and the appliances at command, may be considered as being one of the most skilful engineering works ever completed. This lighthouse, which cost £40,000, withstood the storms of 122 years, when it was replaced, not from any defect or fault of its own, but on account of the wearing away of the rock on which it was erected. The present structure, which is 170 feet high, was erected for the Trinity House by Sir James Douglas, at a cost of £61,500.

Amongst the other principal lighthouses which have been erected on the coast of this country are the Bell Rock in the Firth of Forth, by R. Stevenson, in 1807–11, at a cost of £61,331; the Skerry Vore, by Alan Stevenson, in 1838–44, at a cost of £90,218; and the Wolf Rock at the Land's End, by James Walker, in 1862–69, at a cost of £62,726.

In the earliest beacons the lights were supplied by wood or coal fires burning on the top of towers. Subsequently the open fire was superseded by a lantern lighted by candles. For more than forty years after the erection of Smeaton's Eddystone tower it was lighted by tallow candles placed in hoops, and up to 1811, twenty-four wax candles were used. Even up to 1816, the Lizard Light and that on the Isle of May in the Firth of Forth were maintained by coal fires. Lamps with mirrors were used for beacon lights at the entrance to the Mersey at the end of the last century, and in 1783 oil-lamps with Argand burners and reflectors were introduced into the Cordouan Lighthouse. The great advantage of such a light became so obvious that it was soon after adopted by the Trinity House in this country. The catoptric system, or the reflecting of the light from a bright surface of such a form as to cause all the rays to proceed in one direction, was followed up by the dioptric system, by which the rays are made to pass through lenses, by which they are refracted into the desired direction. The difficulty in obtaining glass of the size required of sufficiently pure quality, and in grinding it to a perfect figure, for a long time delayed the adoption of this system. These difficulties were finally overcome by Fresnel, and a dioptric lens was fitted in the Cordouan Lighthouse in 1822. The construction of these lenses has since been carried to a state of great perfection by Messrs. Chance of Birmingham. In 1835, on the recommendation of Mr. Alan Stevenson, the dioptric system was used for the northern lighthouses, and afterwards by the Trinity House, the first light on this system being a revolving light fixed at Start Point.

The lamps used also have gradually undergone improvement. The oil first used was sperm; this was succeeded by colza, and finally by mineral oil. The power of the light has been increased by using a number of concentric wicks on a system perfected by Sir James Douglas, so that oil-lamps are now used giving lights equal to five thousand candle-power.

The change that has taken place in the amount of light now

given may be realized by comparing the twenty-four wax candles used for illuminating Smeaton's Eddystone Lighthouse at the beginning of this century with the beam of light now sent forth, which is calculated as being equal to 160,000 candles.

Gas is also used as an illuminant. On several of the more important light-stations the electric light has been adopted. For prominent headlands and for lights required to be seen at great distances, this surpasses all other means of illumination.

Breakwaters.—As already pointed out, the progress of engineering science in this country owes nothing to the fostering care of the governing power, the provision of docks and harbours, the improvement in rivers and shipping, having all been done by local authorities, by companies of merchants, or by private traders, without Government aid or subsidies. The only exception to this, except the dockyards and works required for the purposes of the Navy, has been the erection of harbours of refuge. The first of these was that at Plymouth, the breakwaters for which were designed and carried out by John Rennie between the years 1812–41. The piers for this harbour are one mile long, and enclose 1120 acres. They absorbed 3,620,000 tons of stone, and cost one and a half million of money.

Portland Breakwater was built during the years 1847–71, from the designs of J. M. Rendel, and finished under the direction of Sir John Coode. It consists of an outer pier 6400 feet long, and an inner one 1700 feet. It required $5\frac{3}{4}$ million tons of stone, and cost £1,034,000, exclusive of the value of the convict labour which was employed on it.

Holyhead was constructed for the purposes of a national harbour of refuge, and was commenced by J. M. Rendel in 1849, and finished under the direction of Sir John Hawkshaw in 1873. The breakwater is 7860 feet long, and encloses 400 acres. It required seven million tons of stone, and cost £1,285,000. The piers were built in an average depth of seven fathoms.

The only foreign work of this class that can compare for magnitude with those enumerated above is that at Cherbourg. This was first commenced in 1784. The masonry wall above the level of low water was commenced in 1832, and was finished in 1853, thus taking nearly seventy years to complete. The piers have a total length of 12,180 feet, and the foundations were laid in from six to seven fathoms of water. The cost of this structure was £2,674,491.

River Improvements.—The works which have been carried out for the improvement of the principal tidal rivers will be found given in detail in a subsequent chapter, a selection having been made of those that embrace the application to practice of the principles advocated by engineers of experience under the most varied conditions.

CHAPTER III.

THE MOTION OF WATER IN RIVERS.

ALTHOUGH the flow of water in all channels is governed by the same laws, yet, owing to numerous disturbing causes, the consideration of the problem when applied to tidal rivers is of a more complex form than in channels having smooth surfaces and regular dimensions, and in which the inclination is regular, and the flow always in the same direction.

Water is a non-elastic fluid, the particles of which are free to move in every direction.

The term *stream* may be taken as representing a body of water moving in a defined channel, the width being taken as a line at right angles to the direction of flow.

A *filament* is a portion of this stream of very small width, and consists of an indefinite number of molecules or *particles* following one another in the same direction.

The mean velocity is the average rate of forward movement of all the particles of the cross-section of the stream.

The *section* of a stream is the area of a plane taken at right angles to the direction of the forward motion.

The *hydraulic mean depth* is the proportion of rubbing surface to area in the section of a stream, and is thus defined by Robison: If every section be reduced to a rectangular parallelogram of the same area, and having its base equal to the border unfolded in a straight line, the product of this base by the height of the rectangle will be equal to the area of the section, and this height will be a representative of this variable ratio of the section to the border. Every section being in this manner reduced to a rectangle, the vertical height is called the *hydraulic mean depth.* For circular channels, the term *hydraulic radius* is generally used.

The motion of water is due solely to the effect of gravity.

Every individual particle of water is attracted by gravity towards the centre of the earth, and has therefore a constant tendency to seek the lowest point attainable, or that nearest to the centre of attraction. The ultimate progress of the particles is arrested either by the bottom or sides of the channel in which the water is contained.

When water is at rest, the particles of each horizontal layer being equally distant from the centre of attraction, are all in equilibrium. The pressure at equal distances from the surface is equal both laterally and vertically, and the surface of the water is then described as being *level.*

When the surface is not level, some of the particles are nearer the centre of attraction than others. When this is the case, every particle that is further removed than another strives to attain the nearest possible situation, or, as it is generally termed, the lowest place. In this struggle every particle is displaced and put in motion.

In a river having a surface inclination, every particle of the water is therefore in active motion downwards, struggling to reach the lowest point.

The amount of force due to gravity depends on the difference of the level of the surface of the water in a river. This difference in level in any given length is termed the *fall*, or inclination, and constitutes the *head.*

The movement of water and its velocity are therefore governed by the surface inclination of the water, and not by the shape of the bottom of the channel.

If additional water be poured into a channel so as to raise one end of the stream higher than the other, the particles which are at the higher level exert a pressure on those below them, and these, being perfectly free to act in every direction, are pushed downwards, forwards, and upwards towards the lower level. The whole mass of water is thus put in active motion, and continues so until a level surface is again attained. The probable action is shown by the diagram, Fig. 2.

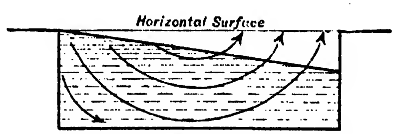

FIG. 2.—Diagram showing motion of water.

That the action is not that of a vertical ascent and descent may be proved by observing the course of sediment stirred up in the bottom of a clear running stream of sufficient depth.

The particles of mud do not rise to the surface immediately over the place of disturbance, but at some distance down the stream, this distance varying with the depth of the water. Experiments made by Mr. J. B. Francis in a canal at Lowell by injecting white-wash through a tube nearly at the bottom of the stream, showed that the particles came to the surface at distances varying from ten to thirty times the depth. The velocity of the water being 3·40 feet per second.

The particles which come in contact with the bottom and sides of a stream, being retarded by the effect of friction, do not move with the same freedom as the others; and are not only retarded in their motion, but also deflected and thrown out of their true course by obstacles arising from the inequalities of the surface, thus causing a further disturbance.

In flowing water the whole volume does not move forward in one mass, as is the case with a solid body, but every individual particle is in motion. As the volume moves forward, these particles roll round one another in orbits varying in dimensions according to the section of the stream. The diameter of the orbit is governed by the distance from the surface of the water to the bottom of the channel and the distance between the sides. In shallow streams the particles are continually circulating in a number of small orbits, rolling round and amongst one another in all directions, according as they are diverted by contact with the sides and bottom. In deeper streams the orbits are larger, and the disturbing agents fewer in proportion. Thus with the same velocity the disturbance to the free flow of the particles decreases as the depth and width of the stream increases, and the diameter of the orbits consequently becomes greater. In other words, the further the centre of a stream is from the retarding medium, the less is the effect of this disturbing rotary motion. This is the cause why a deep stream has a less eroding effect than a shallow one, and why as the hydraulic mean depth is increased the velocity also increases.

The existence of the deep pools which are found in the beds of rivers, the curved motion which a stream assumes, and its power to transport material of heavier specific gravity than itself, are due to this upward and rotary action of the particles of water.

A large volume of water once in motion maintains its flow

with a very slight surface inclination. Thus on the lower reaches of the Danube and the Mississippi, the surface inclination averages only a quarter of an inch in a mile; on the Parana, the current is maintained with an inclination of an eighth of an inch.

If, owing to the action of gravity, water continued to flow in a river with no resistance, it would be subject to a constantly accelerating force, but as its motion over any given length is uniform, there must be also a retarding force. This retarding force is due to the friction of the particles of the water against the sides and bottoms, to the adhesion of the particles of the fluid, to variations in the head and irregularities in the form of the channel causing disturbance to the motion and a loss of living force from the particles being reflected in currents contrary to the general direction of motion, and to turbidity of the water.

The measure of the moving force is expressed by the difference of level over a given length divided by that length (S), and by the force of gravity acting at the end of one second on a body falling freely, $g = 32 \cdot 1908$ feet.

The accelerating force is therefore expressed by the term—

$$\frac{\text{height}}{\text{length}} \times g = \mathrm{S} \times g$$

The retarding force is caused principally by friction. Friction in fluids is independent of pressure, and is proportional to the area and roughness of the rubbing surface, and is the same at all depths. The measure of the resistance of friction and other retarding causes is an unknown quantity only to be determined by observation, and is expressed by a coefficient C.

Resistance is proportional to the square of the velocity with which the water is moving (V^2). When the velocity is increased, the impulse of the particles on any irregularities is increased in proportion, and the number of particles driven against the rough surface is also increased at the same rate; the resistance will therefore increase as the product of the velocity into the velocity (V^2).

Resistance is therefore directly proportional to the extent of the surface of the sides and bed of the channel with which the water comes in contact, and is inversely as the volume; as the resistance becomes so much less when it has to be shared

amongst a greater number of particles. The measure of this resistance is $\frac{\text{area}}{\text{wetted contour}}$, or the hydraulic mean depth (R).

In a stream of uniform velocity, the accelerating force is equal to the sum of the retarding forces. Accordingly—

$$S \times g = R \times V^2 \times C$$

in which S is the fall divided by the length; g, the effect of gravity; R, the hydraulic mean depth; V, the velocity of the water in feet per second; and C, a constant depending on the roughness of the surface and determined by observation.

A decrease of friction causes an increase of velocity.

When the sections of a river vary, the volume of water remaining the same, the mean velocities are inversely as the areas of the sections.

The velocity varies nearly as the square root of the depth.

Velocity increases in proportion to the square root of the surface inclination, the hydraulic mean depth remaining the same. Four times the fall will double the velocity.

The greater the hydraulic mean depth, the greater the velocity. The velocity is at a maximum when the depth of a stream is half the width.

As rivers increase in size the proportion of the retardating to the accelerating force continually diminishes, and they therefore require a less rate of inclination to produce the same velocity.

Where the flow of water in a channel is uniform, the same quantity of water will be discharged at the lower end of any given length as enters at the upper end; consequently the same quantity of water must pass each transverse section per second, the velocity of the current increasing where the area is diminished, and decreasing where it is enlarged.

The velocity of a stream is not uniform throughout the whole section. The contact of the particles with the sides and bottom of the channel retards the velocity of the water immediately adjacent, and as the particles are reflected they transmit this retardation to the more distant particles, the particles nearest the rubbing surface being most affected, and each in succession being less influenced and the retardation decreasing towards the part most distant from the bottom and the sides, being at a maximum at the former point, and a minimum at the latter. The point of maximum velocity is found to be on a vertical line

drawn through the deepest part of the channel and a little below the surface.

There exists a point where the velocity of the filaments of the water is at a mean of the whole depth. This point varies with the depth and other conditions of the river.

Dubuat, as the result of his observations, gave the following rule for finding the mean from the surface velocity. If unity be taken from the square root of the surface velocity expressed in inches per second, the square of the remainder is equal to the velocity at the bottom, and the mean velocity is equal to half the sum of the surface and bottom velocities;

$$\text{or if } \left.\begin{aligned} s &= \text{surface velocity} \\ b &= \text{bottom} \quad ,, \\ m &= \text{mean} \quad ,, \end{aligned}\right\} \text{in inches}$$

$$\text{then } b = (\sqrt{s} - 1)^2$$

$$m = \frac{s + b}{2}$$

$$m = \frac{s + (\sqrt{s} - 1)^2}{2}$$

From a large number of observations made by Harlacher and Richter on the Elbe, the Danube, and other rivers, the mean velocity was found to be 85 per cent. of the surface velocity, and this same result was arrived at by Revy on the Parana survey. Rankine gives the mean velocity as 75 per cent. of the maximum for slow rivers, and 80 per cent. for rapid streams; Beardmore gives 83; Neville, 83 if taken in centre, and 91 if taken in several places. Downing gives a rule for wide streams in which the depth is small compared with the width, that the mean velocity is very nearly proportional to the square root of the depth. Borneman, from observations made on the Rhine at Basle, found that the ratio of the mean and surface velocities on one vertical ranged from 0·7727 to 0·8525, the average being 0·8226, and that the mean velocity of the whole stream was 0·7305 of the greatest surface velocity.

J. Schlichting, from observations on the Elbe near Memel, found that the maximum velocity lies at the surface or very near it (in some few cases he found it a short distance below); that the maximum velocity is directly above the bed, and the mean at four-ninths of the depth above the bed. M. Fontaine,

from observations made on the Rhine at Basle in 1820, found that where the depth was not great the maximum velocity was at the surface, and the velocity decreased insensibly downwards, the decrease becoming more rapid towards the bottom; that the mean velocity was 85 per cent. that of the surface, and the bottom 56 per cent.; and that the position of the mean velocity was at a distance of two-thirds of the whole depth from the top, and half the depth when the bottom was very regular.

The observations made by Gordon on the Irrawaddy, in depths of from 40 feet to 80 feet, and velocities of from 5 to 6 feet a second, showed the point to be, in the large majority of instances, at one-tenth of the depth, varying, however, in a few exceptional cases from two-tenths to four-tenths. Near the banks the point was observed to be lower down. The observations of Major Cunningham on the Ganges Canal showed the point of maximum velocity to be below the surface, falling lowest towards the margins, and the mean velocity at and near the centre.

Messrs. Humphrys and Abbot's observations place the maximum velocity at a greater depth than any other observers, in some cases being at half the depth, and in others at one-fourth. The observations were made with kegs attached by cords to surface floats. Results obtained in this way in depths of from 50 to over 100 feet cannot be regarded as strictly reliable.

Generally, the mean velocity may be taken at 85 per cent. of the maximum, and its position at the centre, or, in deep rivers, at 0·45 of the depth measured from the surface.

The point of maximum velocity is generally a little below the surface on the vertical line passing through the deepest part of the river, the water on the immediate surface being retarded by the friction with the atmosphere.

The minimum velocity is at the bottom, and its proportion to the maximum velocity will be affected to a large extent by the quantity of sediment that is being carried, and the depth of the stream. Rankine gives the bottom velocity as 60 per cent. of the surface for ordinary rivers, and 50 per cent. for very slow currents. Grieve, in observations made on the Oder and the Warthe, found that at depths of about 10 feet the ratio varied from 61 to 55 per cent. Revy, on the Parana, found that, for depths of about 24 feet the ratio was only 35 per cent. Observations made on the Rhine and the Meuse gave the ratio

of bottom to surface velocity as 0·63 in depths of about 10 feet, and 0·57 for depths of about 25 feet.

Generally, then, it may be taken that the bottom velocity varies from about 75 per cent. of the surface velocity for rivers of depths of about 5 feet, to 50 per cent. for three times this depth, and 66 per cent. for large rivers.

In these proportions for maximum velocity no account has been taken for the action of the wind. Gales have a considerable influence in retarding or increasing the surface, and, proportionately the whole, velocity. In estuaries a continuance of wind from one quarter, or heavy gales, considerably hasten or retard the flow of the tides, and cause them to be abnormally raised or depressed, according to the direction from which they come. In lakes and large sheets of inland water, the wind has considerable effect in lowering the water on the windward and raising it on the lee side. Where the volume of the water is large, the effect of the wind does not extend to any considerable degree below the surface. Thus at the outfall of the Rhone in the Mediterranean there exists a littoral current, caused by the wind blowing from one direction. It was found, however, that it did not extend to more than about 6½ feet below the surface, and is not, therefore, sufficient to prevent the deposit of the materials brought down by the river. The observations of Messrs. Humphrys and Abbot on the Mississippi showed that the effect of wind on a river (exclusive of tidal causes) does not reach beyond mid-depth.

The laws governing the flow of tidal water are more complicated than those of rivers in which the stream is always running in one direction. In the former case the direction of flow is continually being reversed, and salt water of greater density than fresh has to force its way against a current coming from an opposite direction. The momentum of the ebb water has not only to be checked and its surface inclination reversed, but a current established in an opposite direction to that which the natural slope of the district and the bed of the river would indicate as the way water would naturally run. In a paper in the *Proceedings* of the Institution of Civil Engineers, Mr. W. R. Browne produced the result of observations taken by him in the river Avon, near Bristol, to show that until about the end of the first quarter of the ebb, on a tide rising 21 feet and a low-water depth of 5½ feet, the water had absolutely no motion at

the bottom of the channel, the surface velocity being 3·57 feet a second; but that after this the lower particles began to move in the same direction as the surface current, until they attained a velocity of about 0·7 that of the surface. As the direction of the water in a tidal stream has to be reversed, there is probably a period of longer or shorter duration of slack water, while the reversing process is in operation. So far as the surface is concerned, it is a matter of common observation that between the time of high water and the commencement of the ebb an interval of slack water occurs, a period seldom reaching half an hour; but it does not seem to harmonize with the laws governing the motion of water, that so long a period of slack water as Mr. Browne's observations showed can exist in tidal rivers.

Mr. Stevenson found that in Cromarty Firth there was an under current at flood-tide exceeding that on the surface. The width of the Firth is 4500 feet, and the depth 150 feet. At the surface the velocity of the water was at the rate of 1·8 miles an hour; at 50 feet deep the velocity was 4 miles an hour. On the ebb the surface velocity was at the rate of 2·7 miles; and at 50 feet, 4·5 miles. In the river Dee at Aberdeen observations showed that, while there was an outward upper current of fresh water, there was an inward current of salt water at the bottom, the surface gradually rising with the influx of the tidal water.

The contour of rivers in their natural condition is never found to be regular, either horizontally or vertically. The course of the river, whether tidal or fresh, consists of a series of curves, and a straight reach of any length is very exceptional. The bed also consists of a series of pools and shallows, which maintain their shape and position without change, although the conditions of the flowing water are continually varying, at one time running with great depth and velocity, and carrying along large quantities of solid material, and at other times running with low velocity and at less depth. Temporary alterations may occasionally occur, and a river may change its course; but where the course remains unaltered, the contour of the bed will be found to remain materially unaltered. Without an investigation of the cause of this, it would seem natural that the heavy material carried by the water in suspension would be deposited in the pools, and that they would become filled up, and the bed raised throughout, in the same manner as occurs at

the mouth of large tideless rivers. After the contour of a river has once been determined, an equilibrium is set up between the erosive action of the water and the resistance of the material of which the bed is composed, and, this equilibrium being once established, the pools are maintained by the rotary action of the flowing water.

It has been already shown that the particles of water never move forward in a mass, but that each particle is deflected from its course by the difference of level of the surface and the irregularities of the bed. The tendency of the particles is to move in a curved or rotary path, in which the whole mass of the water participates. This rotary motion, acting on the sides of the channel, tends to scour away such portions of the soil as are not sufficiently tenacious to resist the action, and gradually a hollow is scooped out. This accomplished, the curved motion of the particles is increased; the filaments of water are driven out of the straight path and reflected on to the opposite bank,

LONGITUDINAL SECTION.

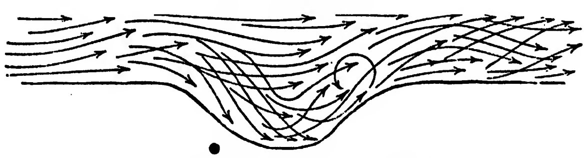

FIG. 3.—Diagram showing motion of water.

and so a series of curves is set up. This motion is shown by the arrows in the diagrams (Figs. 3 and 4). In a pool the particles of water, being reflected vertically, horizontally, and longitudinally,

PLAN.

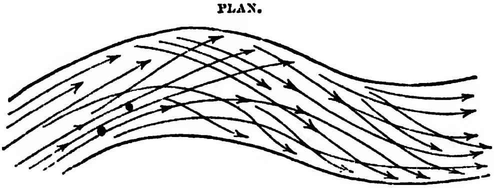

FIG. 4.—Ditto.

are whirled round in every direction, setting up a centrifugal or screwing motion, but always moving onwards as fresh particles of water arrive. This action is increased by the particles having to descend over the edge of the pool at a sharp angle, and then striking the bottom and being reflected upwards. Particles of solid material in suspension in the water are thus

kept in continual motion. As they descend into a pool they are thrown upwards and rolled round, until finally they are caught by the upper current and carried forward.

In flowing water, in addition to the static force which at the same depths presses against the sides and bottom of the channel equally in all directions, there is also a dynamic force depending on the velocity. If the direction of a stream be changed, the particles of water are impelled against the side of the channel, which presents an obstacle to the original line of direction by this dynamic action. The force thus brought into play is absorbed chiefly either in cutting and carrying away the material of which the bank is composed, or, when a state of equilibrium has been reached and the bank is sufficiently tenacious to withstand the impact, in heaping up the water and creating a greater head. In all curves there is, therefore, a radial dynamic action from the convex towards and on to the concave side, causing currents in that direction, which tend to deepen the channel both horizontally and vertically; or else to increase the velocity and raise the surface of the water on the concave side, and to shoal and decrease it on the convex side (see Figs. 4, 5).

TRANSVERSE SECTION.

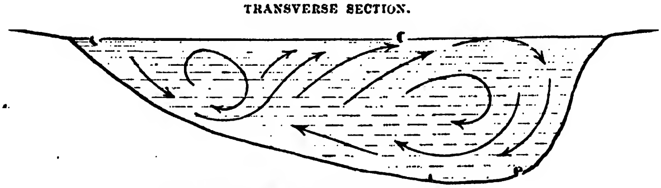

FIG. 5.—Diagram showing motion of water.

A channel which has once attained a state of equilibrium is prevented from being further eroded at the curved portions owing to the varying action of the particles of water as they pass round the curve. When water which is moving along a straight channel comes to a part that is curved, the particles of water which are nearest to the concave side are the first to come in contact with the curved side of the channel, and are thus the first to be deflected from their course. The particles next to these, being later, will collide with those previously deflected, and a similar action will take place as each parallel series arrives. The consequence is that the full force of the water, instead of acting directly on to the hollow side of the

bank and eroding it, will be gradually cushioned by that part of the stream which has already impinged on it. Even in a sandy estuary, if a deep trough be once scoured out, the reaction of the tidal currents flowing up and down and impinging against the sides and bottom will create an eddying or boring action which maintains the trough at its greatest depth and prevents deposit. It is due to this action that the deep pools are maintained, such as the Sloyne in the Mersey, Lune Deeps in the Irish Sea, Lynn Well in the Wash, and the steep mounds of sand with deeps on each side which exist as bars at the mouths of some tidal rivers.

As an instance of the rotary action of water in scouring out the bottom of pools, the following incident may be quoted. An old barge was sunk in the Severn above the weir near Holt, in 10 feet of water, and remained there until the first freshet came, when it was lifted bodily on to the top of the weir, the depth of water not being sufficient to carry it over. In this same reach of the river the bottom of the channel above the weir was scoured out to a depth of 20 feet. The same effect may frequently be found in canalized rivers where the freshets occasionally run with sufficient strength, the deepest water being found immediately above the weir, owing to the water being reflected back from it, causing a rotary and screwing action, which erodes the bottom.

In rivers where the conditions of flow are altered owing to land floods or tides, the transverse surface in a straight reach will be found to be convex when the volume is being rapidly enlarged, and concave when the water in the river is falling. In the former case the velocity is greatest along the axis of the stream, where the depth is greatest and the friction is least; the water then becomes heaped up. In a falling stream, from the same causes, the water passes out of the channel most rapidly along the deepest part. Where the flood or tidal water has spread out laterally, it is thus drawn in larger quantities than it otherwise would be into the channel proper.

Ellet, in his account of the Ohio, states that in all great freshets, when the water is rising, the drift leaves the channel and bends towards the shore; when the surface falls, it recedes from the shore and seeks the thread of the channel. The river, while on the rise, is higher at the centre than at the borders. As the water falls the effect is reversed. The boatmen find that

when the river is falling, the boats and rafts always keep to the centre, and a flat boat will keep its course for a whole day without the sweeps being once used; when, however, the river is rising, the boats are continually being drawn towards the banks.

Baumgarten found that on the Garonne, when the water was rising at the rate of 5 feet in twenty-four hours, with a maximum velocity of 7 feet per second, the water in the middle of the river was 0·4 foot above that on the right bank, and 0·1 foot above that on the left, in a channel 600 feet wide and nearly straight. When the water was falling at the rate of 8 feet a day, with a maximum velocity of 7·5 feet per second, the surface was a plane, being at the right bank a little less than 0·1 foot above its level on the opposite side of the river. From observations made on the Rhine at Basle, it was found that there was a difference of 10½ inches between one side and the other, and the thread of the stream was one inch higher than the lower side.

M. Fontaine found on the Rhine at Basle that the transverse surface of the water varied from convex to concave or horizontal as the river was rising, falling, or slack.

In tidal rivers, as the flood-tide is poured into the channel the surface of the water becomes convex, and it spreads out laterally as soon as it rises above the banks. On the ebb the reverse action takes place, and the water is drawn off the lateral bed into the channel. This description of the condition of the water in a tidal channel is confirmed by observations made on the Seine by M. Franzius.

H. C. Ripley, who was engaged in the survey of the Brazos river in Texas, found the following results, arising from his investigations of the curves in that river:—

1. That the average width of the river was 7½ per cent. less in bends than in straight reaches.

2. The average sectional area was 13½ per cent. greater in bends than in reaches.

3. The average maximum depth was 58 per cent. greater in bends than in reaches.

4. The average hydraulic radius was 24½ per cent. greater in bends than in reaches.

5. The average ratio of the maximum depth to the hydraulic radius was 29 per cent. greater in bends than in straight reaches.

6. The average wetted perimeter was $6\frac{1}{2}$ per cent. less in bends than in reaches.

Thus the average width and wetted perimeter are slightly less, the sectional area is greater, and the maximum depth is decidedly greater, in bends than in reaches.

Velocity Formula.—The relative value of the accelerating and retarding forces was reduced to algebraic terms in a simple formula given by Chezy, which for English measures may be rendered—

$$V = C\sqrt{RS}$$

in which V = the mean velocity, R the hydraulic mean depth, and S the sine of the slope; C being a constant determined by observation.

For pipes or masonry culverts, and in a less degree in open earthen channels of regular section required for drainage or irrigation, where a certain fixed quantity of water has to be delivered within a definite time, a method of computing the velocity is essential, and for this purpose there are formulæ and tables which give reliable results. For a river, and especially a tidal river, with all the varying conditions which attach to such a channel, a formula of this character can only give approximate results.

The section of the channel will vary not only with the movement of the tide, but at nearly every place where it is taken, and the velocity will be continually changing either as the section varies or as the inclination of the surface varies with the range of the tide. Even in a river where the current runs in only one direction it will be found that the inclination of the surface varies in every reach, and that it is exceedingly difficult to select a reach where the conditions are sufficiently favourable to obtain results that will afford figures to enable the discharge to be computed by any velocity formula.

An engineer requires a formula having as few figures as possible, in order that, with little trouble, he may ascertain approximately what the velocity and discharge will be with a given section and inclination of the surface, in any channel with which he has to deal, in the altered condition required for its improvement. The qualifying coefficient to be used must be determined by his own judgment, aided by observations made on such portions of the river he is dealing with as most nearly

approach the conditions of the new channel. The formulæ most applicable to water flowing in earthen channels are given in the Appendix. The one containing fewest figures in working out, and the most generally useful for tidal rivers, is—

$$V = C\sqrt{2RF}$$

where F = the fall per mile in feet, and R the hydraulic mean depth in feet, V being the mean velocity in feet per second.

Approximately, the constants may be taken as follows :—

For small streams discharging about 50 cubic feet a second	0·65
For larger streams of from 200 to 300 cubic feet a second ...	0·75
For tidal rivers 1000 cubic feet	0·85
For „ „ 10,000 „ „	0·95
For „ „ 100,000 „ „	1·00
For „ „ 1,000,000 „ „	1·50

CHAPTER IV.

THE TRANSPORTING POWER OF WATER.

ALL rivers during land floods are charged with a large quantity of alluvial matter which is carried away in suspension, and their turbid condition then testifies to the work that is being done in the transport of material. This detritus is the result of the disintegrating effect of frosts and rains, which break up and loosen the soil sufficiently to allow of its being washed by the rain into the river. On reaching the channel of the stream it becomes thoroughly mixed with the water, and is carried along in suspension. When this material reaches a tidal estuary, it is transported over the sands and deposited near the banks during the time of slack tide, where, owing to the shallow depth, there is little or no scour, causing salt marshes to accrete; or else it is carried out by the ebb current and deposited in the sea.

Flowing water frequently passes along the bed over which it is flowing without exercising the erosive action due to the velocity at which it is running. A very slight cause may change part of this velocity into erosive energy. A slight obstruction placed in the bed of a sandy channel will cause erosion, and the scouring of a pool where previously the water had passed over without any effect. The deep pools always to be found at concave bends are instances of the development of this power.

At certain velocities water has an eroding as well as a transporting power. Under normal conditions the sectional area of a river is sufficient to allow of a velocity slow enough to prevent erosion, and the natural bed of the river remains in a state of stability. If, however, the velocity is sufficiently increased, or any agency comes into play that disturbs the material composing the bed or banks, the transporting power of the water then carries away the soil, and the sectional area becomes enlarged. In the same way detritus brought down at one time and deposited

in a channel may be transported away in floods when the velocity is sufficient to erode and stir it up. Thus, also, tidal currents may flow over sands without disturbing or removing them, but if these sands are broken up by wind or wave action, the sand may be transported by the tidal current into the rivers. Shingle beaches are only found where there is a considerable rise of tide and sufficient wave force is generated to erode the cliffs.

If a stream is loaded to its full carrying capacity, it will not take a greater burden, but flows against the banks and over its bed without eroding them. If, however, it is not overburdened, and the velocity is sufficient to erode, it will pick up material from the soil over which it passes.

The work performed by water in transporting material assumes enormous proportions in some of the larger rivers. For example, the Mississippi conveys into the Gulf of Mexico every year on an average 363 million tons of detritus, equal to a space one mile square and 241 feet deep. The mean proportion of solid matter contained in suspension in the water is as 1 to 1500, the maximum being 1 to 681. In addition to this, the quantity rolled along the bottom is estimated as equal to a mass one mile square and 27 feet deep, or 37½ millions of tons. In the La Plata, the suspended matter carried in suspension past Buenos Ayres every twenty-four hours in the ordinary state of the river was found to be 212,000 cubic yards, equal to 77,380,000 cubic yards in a year. Observations made on the Volga showed that in fifty days, during a flood, the solid matter carried in suspension amounted to 1⅓ million cubic yards. The Nile carries 49½ million tons of solid matter to the sea in suspension in a year of average discharge. The Hooghly is estimated to carry thirty-nine million cubic yards of mud in a single season. The Danube, on an average of years, is estimated to convey nearly sixty-eight million tons of solid matter into the Black Sea; the quantity of matter in suspension varying from 940 to 6 grains in a cubic foot taken from the surface, the mean being 156 grains, or $\frac{1}{2800}$ of the weight of the water; this quantity is carried when the velocity is 1·86 feet per second. The Durance is stated to transport seventeen million tons of earthy matter in a year. When the training walls of the South Pass of the Mississippi were put in, the scouring action due to the concentration of the current removed 70,000 cubic yards in seven days, and 7,607,000 cubic yards in four years. In the Seine, after the training walls were put in, it was calcu-

lated that eighty million cubic yards of materials was removed by the transporting power of the water. As a further illustration of the power of water to transport material, an instance which came under the author's own observations may be quoted. During the dry summer of 1868, silt which had accumulated in the river Witham to the extent of $1\frac{1}{2}$ million tons was washed out by the winter floods in the course of a few weeks, and transported to the estuary seven miles away.

The instance of Dungeness Bay, given by Captain Washington in the Report of the Tidal Harbour Commissioners, may also be quoted, where there was an increase of 430 acres of sand averaging 7 feet 6 inches deep, equal to seven million tons, which had been deposited in thirty-five years.

The quantity of material carried in suspension varies very considerably. In some rivers upwards of two per cent. in weight of the total volume of water passing along the channel consists of solid matter. In the Tees, when the training works were going on, the quantity of material in suspension amounted to nearly 2 lbs. in a cubic foot, or $\frac{1}{32}$ of the weight of the water. In the Durance and the Vistula the proportion in floods is $\frac{1}{48}$; in the Garonne and the Rhine in Holland, $\frac{1}{100}$; the Rhone in floods carries $\frac{1}{230}$; the maximum ever observed being $\frac{1}{45}$, with a mean velocity of the current of 8 feet per second. With this proportion the quantity of solid material carried in each cubic foot of water amounts to $426\frac{1}{2}$ tons a day. In the Guadalquiver the quantity was found to amount to four per cent. Much attention has been given to the amount of silt that can be carried in suspension by the canals in India, with the view of ascertaining the maximum amount of fertilizing matter that can be transported on to the land with a minimum of deposit in the canal, the water in which has a velocity that shall not erode the banks or interfere with the navigation. On the canals fed by the Indus the matter carried in suspension in the water was found to be $\frac{1}{300}$ of the weight, one-third of which was deposited in the canal, leaving $\frac{1}{600}$ as the quantity transported on to the land at a velocity of 3 feet per second; this quantity is equal to 12 tons for every cubic foot of water in twenty-four hours. In the Nile, a velocity of 2 feet per second prevents deposit when the water is much charged with slime; when the velocity is less than 1·8 foot per second, silt is deposited. The quantity carried in suspension amounts to $\frac{1}{674}$ of

the weight of the water. From observations made by the author on the river Welland, in Lincolnshire, when the bed of the river was being mechanically disturbed, and from samples taken four miles below the place of disturbance, the quantity of matter in suspension was found to be $\frac{1}{614}$ of the weight of the water. The rate of current being 3 feet per second. This was equal to 11·8 tons in twenty-four hours in each cubic foot of water.*

Taking the specific gravity of water as 1, the relative weight of coarse river-sand is 1·88; fine sand, 1·52; clay, 1·90; alluvial matter, from 1·92 to 2·72. A cubic foot of water weighs 62·5 lbs.; of coarse sand, 117·5 lbs.; fine sand, 95 lbs.; clay, 118·75 lbs.; alluvial matter, 120 to 170 lbs.; silt, 103 lbs.

The matter to be transported, being much heavier than the water, will pass from a state of suspension to that of deposit when the water in which it is contained ceases to be in motion. A solid particle, being of greater density than the water, is continually tending to sink, the time occupied being proportionate to its size and specific gravity. The particles of water in running streams have, however, a considerable upward motion, which is sufficient to counteract the downward tendency of the solid particles. Thus particles of considerable size may remain in suspension for long distances, while the finer particles may be altogether prevented from sinking. The motion of water in running streams is never uniform, and the relative position of the suspended particles is constantly being changed. The direction of the particles is altered by the varying form of the bottom and sides, by impediments met with on its course, and by the varying velocity of the whole mass due to the friction of the sides and bottom, and of the individual particles of water. Continual eddies and miniature whirlpools are constantly being generated, by which a rotary motion is given to the water. The particles of matter in suspension are carried forward by the velocity of the current and thrown upwards by the eddies, and thus kept from sinking to the bottom. The bed of a river is rarely regular, but consists of a series of pools and shoals, which have the effect of continually altering the direction of the particles of water. Even where the bed approaches to a level surface it frequently contains a series of ridges, composed of

* The quantity of material carried in suspension in different rivers will be found in the Appendix.

the deposit in transit. These ridges have almost invariably a gentle slope on the upper side, with a more vertical inclination on the down-stream side. Even where the material is sand, the down-stream side often presents an almost vertical face, over which the moving particles are rolled. These ridges are constantly altering their form, due to the changing size of the particles rolled along, a single pebble often altering the whole shape of the moving detritus.

If the velocity of the stream be checked by a widening of the channel, the motion of the water becomes less disturbed, and a portion of the matter in suspension is deposited, the quantity depending on the variation in the velocity of the current. This deposit reduces the area of the channel, and tends to restore the normal velocity. A slight retardation of the current, however, does not necessarily produce a deposit. Increase in depth does not cause deposit in the way that increase of width does. The particles of water in the latter case, descending on one side of the deep and rising on the other, cause a rotary or centrifugal motion in the hollow; the particles of matter brought into the depression are rolled round and directed upwards, and ultimately carried off by the film of water moving above the surface of the pit.

When the water is highly charged with deposit, the greater amount will be found at the bottom and the least at the surface. When it is undercharged, the distribution is more general, the amount at any point being determined by the greater or less disturbance of the particles due to eddies and whirlpools. In the Rhone delta, where the water was very highly charged, the proportion was found to be as 100 at the surface to 188 at the bottom. In the Mississippi, in its ordinary condition, the proportion was only 147 to 188. In a sandy estuary, where the water was much undercharged, the author has found the proportion to vary as 8 to 14 and 12 to 28.

The power of water to transport solid matter depends on the velocity—modified by the depth—which governs the transporting power in two ways: One certain, when, the quantity of water being constant, the amount of material carried will vary directly as the velocity, and as affected by the time that gravity has to act on the particles while travelling a given distance. The other uncertain, and due to the increase of eddies and whirling motions set up by the increased momentum of the

stream. With regard to the first, if a given quantity of water carries a given quantity of material in suspension, it is obvious that by increasing the pace throughout the whole of the channel the quantity of material carried must also be increased. It is, however, impossible to lay down any rule for the second factor, as it must depend on the contour of the channel and the means for setting up the whirling or rotary motion that keeps the particles in suspension.

The weight of sand and pebbles when immersed in water being only about half their weight in air, these materials are more easily transported by currents of moderate velocity. Sand or pebbles lying on the bottom of a river present an obstacle to the free motion of the particles of water and check their momentum. They are therefore acted on by the dynamic force of the flowing current in addition to the transporting power due to the velocity alone. It is to this cause that pebbles and shingle are moved along a beach by tidal currents of small velocity, and, when aided by the disturbance caused by waves, stones of very considerable size are brought from deep water and left stranded on the shore. The momentum contained in the deep water of the sea, due to the tides aided by the current acting on heavy bodies in a partial state of flotation, carries these along and lands them in a position from which the returning wave has not power to move them.

It has been shown in a previous chapter that the particles of water of which a running stream consists are continually rolling round one another in circular orbits, and that the size of these circles depends on the depth of the stream. The deeper and wider the stream the less the rotary motion is impeded. The smaller the diameter of the orbits described by the particles the more disturbed is the condition of the water and of the particles of solid materials which it contains, and therefore the greater the ability of the water to retain these in suspension, and the more the energy expended in rubbing and eroding the sides and bottom of the channel. The larger also the diameter of the circle through which the particles move the more easily they will glide over the surface, and the shallower the water the more direct, frequent, and effective will be their impulse. The greater agitation in which shallow water is kept increases its capacity to hold matter in suspension and to erode its bed. The strength of the stream is absorbed proportionally in this

action, and the velocity accordingly diminished. This is no doubt the cause why shallow streams frequently erode the soil of their beds and banks, while deep water passes on over the same kind of soil without exercising the same effect.

It has been stated that a shallow stream running at a high velocity has less effect than the scouring and transporting power of a deep stream having less velocity, and that the greatest effect is produced when the mass and velocity are at a maximum. If, however, the above be a correct description of the motion of water, this would not be the case. The author has frequently observed the action of moving water running over sand in a tidal tank, and has invariably found that the greatest movement of the sand took place on the first of the flood and the last of the ebb; and that if the particles of sand were perfectly quiet when the water was deep, movement began to take place as the water shoaled towards the end of the tide, the movement of the particles being reversed on the flood, but ceasing as soon as the water acquired any depth. It is stated by Mr. Corthell, as the result of observations on the Mississippi works, that the conclusion arrived at was that the ability of a stream to carry material depended on the velocity modified by the depth, and that the power to keep the sediment in suspension was inversely as the depth. General Eads, in his investigation of the currents of the Mississippi, came to the conclusion that the quantity of matter which a stream was able to carry increased as the square of the velocity, and the author believes this assumption to be correct. Mr. W. Airy has calculated that the capability of a stream for moving substances varies as the sixth power of its velocity. That is to say, that in the case of a stream moving with a velocity of 8 feet per second, if the velocity be increased to 9 feet, the increased velocity would move particles double the weight that it would before; or if the current were doubled, it would move particles sixty-four times the weight that it did before. This formula was based on the assumption that the particles were cubes sliding along the bed of the river. Mr. H. Law confirmed this view, and considered that it would be equally true if the particles were either cubes or spheres, and if, instead of assuming the cube to slide, it was assumed to be rolled over on its edge. When cohesion came into play this law no longer held good, and then the power of the stream to tear up the river-bed would be as the square of the velocity; in this case the

depth has also to be taken into account. Much the same result as to the scouring power of water had been arrived at by Mr. Hopkins, of Cambridge, who calculated it as being in proportion to the seventh power of the velocity. These calculations do not apply to the transport of the material in suspension or the quantity actually scoured, but to the size of loose particles having the same specific gravity turned over or rolled by the stream.

The velocity of running water is checked by the amount of material carried in suspension. The specific gravity of detritus being greater than water, greater work has to be done; the propelling force due to gravity remaining the same, retardation must therefore take place. Clean water will be found to cause erosion where, when the water is highly charged with sediment, no erosion will take place. On the Ganges Canal, when the water passing through is highly charged with deposit it is found that a certain amount of deposit takes place, but this is picked up and carried away when the water becomes clean.

The material transported by rivers consists either of alluvial matter, clay, sand, or shingle. The first two, owing to the fineness of the particles, are easily transported in a state of suspension. When sand is disturbed, a certain portion, consisting of the very finest particles, is carried away in suspension, but all particles sufficiently large to be visibly angular, as also shingle, require a greater velocity of the current to move them, and their transport is effected by being rolled along the bottom. Although clay will not yield to such a velocity as generally prevails in navigable rivers, if it be disintegrated the particles easily mix with the water and are carried away. The author has found, as the result of observation and experiment, that the most effective results may be obtained by mechanical disintegration and mixing from warp or alluvial deposits, then from clay, and the least effect is obtained from sand.

The quantity carried in suspension at a given velocity is not wholly in proportion to the specific gravity of the material, but depends more on the fineness of the particles. Even in still water it will be found that the relative time occupied in settling does not vary as the specific gravity of the materials.

The following table shows the relative weight of different materials when dry, the time occupied in settling in a test-tube, and the quantity of solid matter deposited. The experiments were conducted by means of a wooden trough 12 feet long,

having a channel formed in clay. At the upper end was a small reservoir, in which the different materials to be operated on were placed. These were disintegrated and kept in motion by a cutter 4 inches in diameter, having four fins or blades placed above the cutter. A constant stream of water was supplied from a pipe, the velocity of the water down the channel being at the rate of one foot per second. The two specimens of clay were put in the reservoir in solid lumps, and rammed down before being acted on. Half a gallon of water in each case was taken from the effluent at the lower end, and the matter in suspension allowed to deposit. The water was then drawn off by a syphon, the sediment dried by means of a spirit-lamp and weighed. Where the deposit was small, it was strained through filtering-paper and weighed with the paper. Equal portions of all the dried material were then mixed with water and allowed to settle in a test-tube. The result from the clay is small in proportion to the warp, as it had to be disintegrated. The whole of the clay sent into the stream was carried away in suspension. The deposit obtained from the river sand resembled warp more than sand, the angular particles of the sand being left in the channel and only the finest particles being carried away in suspension.

Material.	Time taken to settle, No. 1 being taken as the unit.		Proportionate weight when dry, No. 2 being taken as the unit.	Proportionate bulk when dry.	Quantity contained in 1 cubic foot of water.	
	Min.	Proportion.			Weight lb.	Proportion.
1. Very fine sand	0·166	1	1·60	—	—	—
2. Deposit from coarse river sand	0·24	144	1·00	1·00	0·323	1.00
3. Deposit from river sand screened fine	0·35	210	1·20	1·00	0·391	1·21
4. Alluvial deposit...	0·35	210	1·11	4·80	1·81	5·60
5. Brick clay	0·38	228	1·18	1·20	0·448	1·38
6. Boulder clay	0·39	234	1·00	1·10	0·783	2·42
7. Alluvial deposit from Tilbury Dock	0·54	324	1·12		12·90	39·94

Mr. T. Login, from experiments recorded in the *Philosophical Transactions of Edinburgh,* gives the rate of sinking in water in feet per minute of different materials as follows:—

	Feet.
Brick clay	0·566
Fresh-water sand	10·00
Sea sand	11·707
Pebbles size of peas	60·00

The clay was mixed with water and allowed to settle for half an hour.

The data generally quoted as to the movement of material by water running at different velocities are based on experiments made by Dubuat. These experiments were conducted in troughs of small scale, where the irregularities of a natural river were absent. They are as follows:—

	Feet per second.		Miles per hour.
Semi-fluid mud was moved by a velocity of	0·25	...	0·17
Soft clay	0·50	...	0·33
Coarse sand	0·75	...	0·50
Sea shingle 1 inch in diameter	2·16	...	1·35

Mr. Login found that in a channel half an inch in depth the current required to move different materials was as follows:—

	Feet per second.		Miles per hour.
Brick clay, after being dissolved in water	0·25	...	0·170
Vegetable soil	0·83	...	0·56
Fresh-water sand	0·66	...	0·454
Sea sand	1·11	...	0·752
Pebbles size of peas	2·00	...	1·37

The experiments made by Mr. Blackwell proved that gravel half an inch in diameter moved with a current of from 2·25 to 2·50 feet per second. Messrs. Humphrys and Abbot found that a velocity of 0·5 foot per second was sufficient to transport the material deposited at the mouth of the Mississippi. Mr. Mullins, in the canals in India, found that alluvial soil was moved by a current of 2 feet a second, and gravelly soil with 3 feet. Captain Washington found that in Dover Bay a tidal current of two and a half knots held in suspension 473 grains of material in a cubic foot of water; a half-knot current, 30 grains; and at slack-water calm there was from 20 to 30 grains of material in suspension. The material was composed of half fine sand, a quarter chalk, and a quarter vegetable matter. The maximum quantity, 473 grains, was found at high water of spring tides during strong off-shore winds, at 20 feet below the surface and 16 feet from the bottom.

It is also stated, on the authority of Dubuat, that sand travels at the rate of 1 foot in 1·26 hours. The author has made a number of observations as to the movement of sand in the experimental channel already referred to. A stream of water, being

fed in at the top end, was allowed to run down the channel with a velocity of 1 foot per second. A continuous supply of coarse river sand was gently mixed with the water in the reservoir at the top end. The sand was not carried by the water in a thin film spread over the whole length of the channel, but advanced in a layer about half an inch in thickness, the down-stream end having

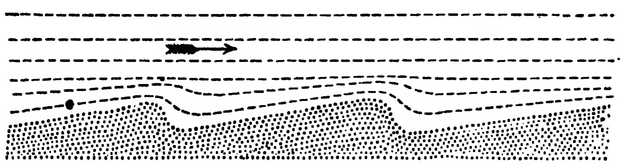

FIG. 6.—Diagram showing movement of sand.

a vertical face over which fresh particles were continually rolled, as shown in Fig. 6. This face advanced forward at the rate of 1 foot in 4½ minutes. When, however, only a limited quantity of sand was put in at the top end and no fresh supply added, the water rolled this along the channel in the same way as before, leaving the up-stream side clear of sand, and the fall on the down-stream side advancing at the rate of 1 foot in 1 hour and 17 minutes, which agrees closely with the result given by Dubuat.

CHAPTER V.

THE TIDES.

THE conditions of a tidal river are that it has a regular flow and ebb, altering in time according to the age of the moon, the rise being higher near the time of full moon and change, and less at the quarters. As a rule the ebb and flow occurs twice in a day, but there are exceptions to this.

Although the terms "fresh" and "salt" water are sometimes applied to distinguish between the two classes of river, it is not necessary that the water throughout the whole of a tidal river should be salt. In the upper reaches the fresh water is driven back by the tide, and in some cases, during heavy land floods, the water continues fresh down to the mouth.

The tidal portion of a river is deemed to extend up to that point at which the water is affected by the ordinary rise of a spring tide, and not to the part only occasionally affected by extraordinary high tides.

All land covered by the tides at high water is deemed in this country to belong to the State, unless it has been alienated. The level of high water for this purpose is taken as being the mean level, both at springs and neaps, ascertained by taking the average level of high water at the place in question during a year or other considerable period of time.

Tides are not only a great commercial benefit to the country through which they pass, but also confer considerable sanitary benefits, especially when passing through thickly populated districts. The daily ebb and flow of the water acts as a great ventilator within a certain distance, bringing up the fresh air and ozone of the sea on the flood; and carrying away on the ebb impurities which otherwise would remain and pollute the river in dry seasons.

To realize the advantage which a tidal river confers, it is only

necessary to compare some of the largest rivers of the world discharging into tideless seas with the tidal rivers of this country.

The Nile, one of the largest rivers in the world, is only navigable for small craft of light draft.

The Mississippi, draining one and a quarter million square miles, or two hundred times as much as the Thames, and which is 50 feet deep a few miles from its junction with the Gulf of Mexico, had only a navigable depth of 13 feet at its outfall before it was improved.

The Danube, draining 316,000 square miles, which is 50 feet deep above the delta, had in its natural condition only a depth of from 7 to 12 feet along the best of its outlets.

The Rhone, which is 42 feet deep at four miles above its mouth, has a depth of 6 feet, and has only been rendered navigable by means of a canal connecting it with the sea.

The Neva, which is 65 feet deep at St. Petersburgh, had only a depth of 13 feet at the lower end.

The Volga, which is the longest river in Europe and drains 562,500 square miles, has only a navigable depth of 8 feet at its outfall into the Caspian Sea.

On the Thames, the Humber, the Severn, and the Mersey, owing to the tidal flow, a channel is maintained by natural causes along which the largest commerce of any ports in the world is conducted.

By the aid of tidal rise, ships are also able to pass along rivers which otherwise would not be navigable for long distances inland, thus economizing the cost of distribution of their cargoes. The port of London, on the Thames, is situated 46 miles from the sea; Hull, on the Humber, is 23 miles, and Goole, 46 miles inland; Bristol is 50 miles from the sea Channel; Rouen, on the Seine, is 77 miles; and Hamburgh, on the Elbe, 60 miles; Antwerp, on the Scheldt, 45 miles; Rotterdam, on the Maas, 20 miles; Bourdeaux, on the Gironde, 75 miles.

There are throughout the world numerous rivers and harbours on the coast that owe their usefulness for commercial purposes, or as fishery stations, solely to the tides. Thus the Avon, leading up to Bristol, has not a navigable depth of more than 3 or 4 feet at low water, yet at high water steamers of over 2000 tons can get up to Bristol.

Tidal rivers possess very great capacities for improvement. The amount of tidal water is unlimited. By the aid of engineer-

ing works, judiciously carried out, the depth of the navigable channel and the distance it extends inland may be very largely increased.

Before, however, such works are undertaken, it is essential for their success, not only that a thorough knowledge of tidal phenomena and of the action of the tides in general should be possessed by the engineer to whose care the river is committed, but also that he should make himself master of all the tidal peculiarities common to the river to be dealt with.

Tidal Terms.—The word "tide" is used to denote the action of the water of the ocean and in rivers and estuaries in rising and falling, which occurs on these coasts twice every day.

The time at which a tide occurs and the height to which it rises vary from tide to tide. The variations are known as *spring tides* when the water is at the highest, and *neap tides* when at the lowest.

As the tides fall from springs to neaps, they are said by mariners to "be taking off;" and when rising from the neaps, to "be coming on," the stage between the two being known as *half-spring tides.* The time of high water is frequently spoken of by mariners as the "time the tide flows." The rising tide is described as "the flood," and the falling tide "the ebb."

As high water of spring tides rises higher than that of neaps, so the low water of springs generally falls lower.

In speaking of the rise of the tide, whether springs or neaps, it is understood to mean the vertical rise above mean low water of spring tides.

The *range* of a tide is the vertical difference between the low water and high water of that particular tide.

Half-tide is the mean distance between high and low water of springs and neaps. In the upper reach of a river where the rise is small, half-tide level means the mean level at the mouth of the river.

Mean Level of the Sea.—Although the height to which the water rises and falls at different parts of the coast varies very considerably, yet there is a mean level to which, at a certain state of the tide, the water of the sea attains. From the levels taken and observations made for the Ordnance Survey, the mean level of the sea round the coast of England varies 15 inches above and below the mean level at Liverpool as adapted for the Ordnance datum. (See Appendix.) According to in-

vestigations made by the French Government, a mean level also extends throughout the coasts of France, Germany, and Holland, the variation being from 6 to 8 inches above and below the standard datum. (See Appendix.)

The diagram in Fig. 7, taken from the Admiralty Tide Tables, will make the different positions of the tide more clear.

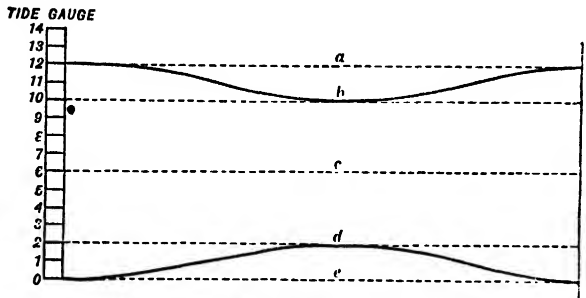

FIG. 7.—Diagram showing range and rise of tides.

a shows the mean level of high water of ordinary spring tides.

b, the mean level of high water of ordinary neap tides.

c, the half tide or mean level of the sea both at springs and neaps.

d, mean level of low-water neap tides.

e, ditto spring tides.

e to *a*, shown as 12 feet on the gauge, the rise of the spring tide or mean spring range.

e to *b*, shown as 10 feet on the gauge, the mean rise of a neap tide.

b to *d*, shown as 8 feet on the gauge, the range of a neap tide.

Theory of the Tides.—The direct connection between the moon and the tides has been a matter of common observation from the most ancient times. Mariners and persons living on the coast could not fail to observe that, with the same regularity as the moon rose above the horizon, crossed the meridian, and again disappeared, the water in the ocean rose and fell; that when she gave the greatest amount of light at night, or at the times when she was almost entirely invisible, the water reached higher up the beach than during the intermediate periods, and that the increase and decrease in height followed regularly the varying phases of the moon; that the time of high water got later every day as the moon got older; that at the equinoxes the tides

attained their greatest height, and were lowest in summer; and, further, that the time of high water varied at every different port.

But while these facts were then realized, the laws which explained the direct connection between the tides and the heavenly bodies were not developed until Newton reduced the knowledge of universal gravitation to a practical form; and the study of the tides, aided by a systematic collection of data, enabled the variations at different ports to be traced to their origin.

The connection of the sun with the tides is not so apparent as that of the moon, but its action as a tide-producing agent was equally well known to the early astronomers.

It is, however, even at the present time, hardly sufficiently realized that although the tides on our shores are caused by the sun and the moon, yet that this is not due to their immediate effect on the waters of the seas surrounding the coast, but upon that of an ocean several thousand miles distant. Also that the tidal current which flows through London Bridge, or up any other river, is due to a wave generated in the Southern Ocean 60° south of the equator, which spreading its influence from this ocean in to the Atlantic, causing a disturbance of every particle of water in that great ocean to a depth estimated in places of more than four miles, thence, extending round the coast of these islands and down the North Sea, until it finally reaches the Thames, more than 7000 miles distant from the source of generation, in about a day and a half; where it causes an elevation in the surface of the river eight times greater than the variation of level of the ocean in which the wave was generated.

For the purpose of explaining the action of the sun and moon in producing the tides, the earth may be regarded as a solid sphere, or, more correctly speaking, an oblate spheroid, the polar diameter being about $\frac{1}{300}$ less than the equatorial. The external portion of this solid sphere that is partly covered with water extends over 144½ millions of square miles, the area of land not covered with water being calculated at 52½ millions of square miles. The depth of the water varies from 4655 fathoms, or more than five miles, in the deepest part of the Southern Ocean, to less than 40 fathoms in the shallowest seas of the North.

This water is not evenly distributed. South of the equator, between latitudes 40 and 70, is a broad belt completely encircling the globe about 2000 miles wide, except in one place, where it is diminished to about one-third this width, and averaging about

$2\frac{1}{2}$ miles deep. Extending out of this Southern Ocean at right angles are three seas, the largest of which, the Pacific, extends to the northern Arctic regions, being connected with the Polar Sea by the narrow channel of Behring Strait. The Atlantic is a less open sea, but it is continuous to the Arctic seas. The smaller of the three, the Indian Ocean, only extends to 20° north of the equator, but is connected by a series of narrow channels at the north-east side with the Pacific. A belt of water also runs nearly round the northern part of the globe, its width being contracted by the projection of Greenland, but round the southern shores of which its continuity is effected. This sea may be taken as averaging 700 miles wide. Scattered over the globe are some smaller seas, some of which have no communication with the main ocean, and the largest of which only has its length in an east and west direction.

By the laws of gravity, the earth, in common with the other planets, is attracted to the sun. There is a mutual attraction between the earth and the moon, and the earth has an attractive force of its own.

The attractive relation of the earth and the moon, and of the other planets to each other and to the sun, is directly proportionate to their respective masses, and inversely as the squares of their distances. The effect of the other planets on the earth as tide-producing agents is so small that it is disregarded.

The effect of terrestrial gravity is to draw every particle of which the earth is composed to its own centre. The tendency of the attraction of the sun and moon is to draw the particles of the earth towards them.

The particles of the solid earth have sufficient cohesion to resist disturbance; the earth is therefore attracted as a whole, the line of attraction from the sun and from the moon passing to the centre. Although the earth is thus attracted as a whole, the amount of attraction varies owing to the sun and moon being more distant from some parts of the earth than from others. The particles composing the fluid portion of the earth have so little cohesion that they are free to obey any disturbing agent, and under its action to change their position, and consequently the form of the water. If the influence of the sun and moon were absent, every particle of the water, being drawn to the centre of the earth by the attraction of gravity, would be in equilibrium, and the fluid would assume a spherical form. If

from any cause the water was disturbed, and one portion raised above the other, the particles in the highest part, being removed further from the centre of the earth than those in the lower part, would be pushed or drawn towards the lower part by gravity, and would endeavour to re-establish the equilibrium. This is what is understood by water being level. The surface of a level plane of water is not that of a straight surface prolonged indefinitely, but one curved to the shape of the earth, every particle in each layer of water being equally distant from the centre.

The moon and the sun act as disturbing agents in preventing the terrestrial equilibrium of the water. The particles composing the fluid covering of the earth, being at unequal distances from these disturbing agents, gravitate unequally.

The power of terrestrial gravity to draw the particles of the water to the centre of the earth is reduced by the attractive force of the moon or the sun, each of these forces acting in opposite directions to that of terrestrial gravity.

The attractive force of the luminaries is at its maximum at the meridian or part directly under them, and diminishes to the horizon, and is less at the nadir than at the zenith. The water, therefore, being drawn up by the luminaries and pressed laterally by terrestrial gravity, assumes the form of an elliptical spheroid, having its major axis directed to the luminaries, and its poles in those points which have them in the zenith or nadir.

The two sides consequently are flattened, being drawn in, the two lowest points of the depression being opposite to one another and perpendicular to the poles of the major axis. The surface of the spheroid has thus two points of elevation and two points of depression, equally distant, in its circumference. Before, however, this spheroid has time to assume its true shape, the position of the disturbing forces is moved by the earth revolving on its axis, the poles, however, continuing to be directed towards the luminaries. The two elevations and depressions, or crests and troughs of the waves, are therefore continually directed to different parts of the circumference of the globe, making a complete circuit with every revolution of the earth.

Such an effect as here described cannot be instantaneous. Time must be given for the inertia of the water to be overcome, and the rise and fall of the water under the luminaries must be gradual. The motion being once given, there is a tendency for the undulations created to continue, until finally checked by

the adhesion of the particles of water and the friction. The recurring force of the tide-producing agents checks this tendency and keeps up the undulation. The consequence is that the form which the waters would assume due to the action of the tide-producing agents is never exactly attained, and would not be even if the whole earth were covered with water.

The actual effect of this tide-producing agency on the belt of water running round the earth in the southern latitudes is to create two vast undulations. The crests of these undulations are of unequal heights and about 5400 miles apart, and move always in one direction from east to west, performing the circuit of the earth, and arriving at the same meridian again in 24 hours 50 minutes.

Each of these crests respectively passes the seas which communicate with the Southern Ocean in a little more than 12 hours, and communicates its influence to, and alternately raises and lowers, the water in them, thus causing the ebb and flow of the tide. The actual disturbance of the equilibrium of the water in this open ocean does not amount to more than about 2 feet when acted on by both luminaries when in conjunction, and to 9 inches when in opposition.

As the action is due to the effect of gravity acting throughout the whole mass of the water, every particle is set in motion from the surface to the bottom.

The momentum given to such an enormous mass of material is something stupendous, and can hardly be realized, even when its effect on our shores is considered.

The moon travels round the earth in the course of 27·33 days, and, her orbit being elliptical, she is sometimes nearer to the earth, or in *perigee*, and sometimes further away, or in *apogee*. The effect on the water of the earth accordingly varies during her transit.

The earth, with the moon, revolves round the sun in a year, and, her orbit also being elliptical, is sometimes nearer to the sun, and at other periods of the year further away. The periods of *perihelion*, or nearness, are at the equinoxes in March and September; and she is furthest away, or in *aphelion*, at midsummer. At these times the attractive force on the earth is at a maximum or minimum.

During these periodical movements the sun and moon are either in conjunction, or both acting in the same direction on

the earth; or in opposition, being then at right angles to one another.

The sun, by the variation of its distance from the earth, also affects the progress of the moon in her journey round the earth, at times diminishing, and others increasing, her attractive force and her effect as a tide-producer.

At new or full moon, or at *full and change*, as it is generally termed, the solar and lunar tide having the same axes and the same poles, their combined effect on the water of the earth is at a maximum, the solar tide being superimposed on the lunar tide; consequently high water is raised higher, and low water depressed lower, and *spring tides* prevail. At new moon the sun and moon are in the same part of the heavens, and exercise their combined force on the same side of the earth. At full moon they are on opposite sides, and the attractive force is not so effective as at new moon. The full-moon tides are consequently less than those due to the new moon.

When the moon is in quadrature, or at 90 degrees from the sun, the sun and moon are acting on the water in opposite directions, and the crest of the lunar wave is superimposed on the trough of the solar wave. The sun then acts as a drawback to the tides, and the effect is as the difference of their attraction. The tides are then raised to the least height, and low water is the least depressed. These are *neap tides*.

From the time of conjunction the lunar lags behind the solar wave until the quadrature, when high water of the moon coincides with low water of the sun, and six hours later in the day than at new or full moon.

The relative position of the sun and moon to the earth is shown in Fig. 8.

The action of the sun and moon in producing a change of form of the water of the earth is inversely as the cube of their distances. The mass of the sun is about 26 million times greater than that of the moon, but the distance from the earth is 386 times further removed than the moon. The effect of the sun as a tide-producing agent is $\frac{26{,}000{,}000}{386^3} = 0{\cdot}445$ that of the moon, or less than half.

Taking the whole tide-producing agency as represented by the figure 3, the sun's share is approximately 1, and the moon's 2.

The tide day is always of greater length than the solar day.

While the earth is completing a revolution round its axis, the moon in the meantime has advanced a certain distance along her orbit, and it takes on an average 24 hours 50 minutes for

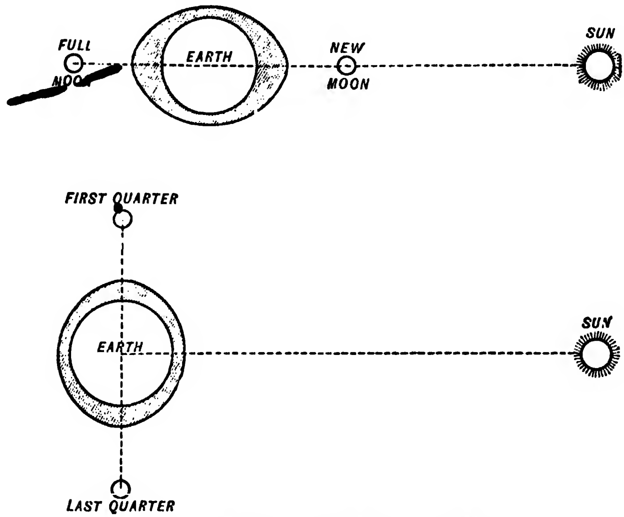

FIG. 8.—Diagram showing position of sun and moon.

the same meridian to again come opposite the moon. The time of high water is, therefore, on an average 50 minutes later every day. This is termed the *lagging* or *priming* of the tides, according as it is referred to the solar or lunar time.

Owing to the progress of the moon along her orbit not being always at the same rate, the variation in the interval between two tides is not always the same. It is least at the syzigies, or the time of new or full moon, and greatest about the quadratures, the extreme variation being from about twenty to forty minutes. The increase is gradual from the syzigy towards the quadrature.

The mean interval between successive high tides being thus more than twelve hours, it follows that on two days on each lunation, or period between one new moon and the next, there is only one high water during the twenty-four hours constituting the solar day.

Besides the changes in the time and height of the tides which take place from day to day, there is a difference in the height of the lunar and anti-lunar tides which occur on the same day. Theoretically, the anti-lunar tide would be less than the lunar.

The position of the moon owing to her declination also affects the height of the two tides, the general rule appearing to be that south of the equator when the sun has south declination, and north of the equator when his declination is north, the day tides are the highest, and that in both hemispheres the day tides are the highest in summer and the night tides in winter. The effect of the declination of the moon in causing a variation in the lunar and anti-lunar tides does not, however, appear to hold good generally, being modified by local causes. In this country about two-thirds of the morning tides are highest, but throughout every month of the year, and both when the moon has south and north declinations, some of the evening tides are the highest. The difference between the two is in proportion to the height to which the tides rise at any particular port, and being greater at the times of the equinoctial tides. At Liverpool the maximum calculated difference, as taken from the tide-tables, varies from 14 inches to 27 inches, the mean maximum inequality between the two diurnal tides being 21 inches. At Hull from 6 to 11 inches, the mean of the maximum difference being 9¾ inches, and the mean difference throughout the year being 4 inches. Taking the average of the night and morning tides as recorded at Boston Dock over two years, the night tides average 2½ inches higher than the morning tides, the average maximum difference between two succeeding tides being 14 inches.

From the particulars given in the Admiralty tables, the diurnal irregularity at other ports throughout the world does not appear to follow any general law. The diurnal inequality becomes so great at some places as to cause only one tide in the day, as in the Gulf of Mexico, at Sawakin in the Red Sea, and at the Solomon Islands in the Pacific. On some parts of the coast of Australia, where the tides are much influenced by the wind from July to December, the evening tides are 2 feet higher than the morning tides, and in October and November the reverse is the case. At Sydney the evening tides are 2 feet the highest in June and July, and the reverse in December and January. At Aden, Karachi, and Bombay, and some other ports on the Indian coast, there is a difference of one and a half to two hours in time, and 1 foot in height between the evening and morning tides. At the Seychelle Archipelago the difference is 2½ feet.

In other places the inequality affects the low water more than high water. At Prince Edward's Island low water varies between $3\frac{1}{2}$ inches to $3\frac{1}{2}$ feet, and at Singapore the low-water level varies 6 feet.

As regards the tides of new and full moon, the former under normal conditions are invariably the highest. Taking an average over a year of three ports on different sides of the coast, the new moon tides are 4 inches higher than those of the full moon.

The tides which reach the coasts of the earth during the course of a year are thus due to a number of disturbing causes arising from the varying distances, at different periods, of the tide-producing agents, and of the changes of certain elements in their orbits. The tidal wave may therefore be regarded as the result of the superposition of a number of smaller waves generated at different periods and of varying amplitudes.

In addition to the ordinary disturbance caused by the lunar and anti-lunar and solar and anti-solar influences, Sir W. Thompson has enumerated the following as having to be taken into account in calculating the period and height of the tides:—

The lunar monthly and solar annual	2
The lunar fortnightly and solar semi-annual	2
The lunar and solar diurnal due to declination	4
The lunar and solar semi-diurnal	2
The lunar and solar elliptic diurnal	7
The lunar and solar elliptic semi-diurnal . ..	4
The lunar and solar declinational semi-diurnal	2
	23

The tidal effects in actual operation vary very considerably from the theoretical conditions which have been described. It has already been pointed out that there is only the narrow belt of the Southern Ocean where the luminaries can freely act in generating the tides. It is not possible to ascertain with any degree of accuracy the amount of elevation and depression that takes place in the open sea. It is only on the coast where this can be ascertained. The observations which have been made in the Southern Ocean are of too limited a character to allow of the movement of the tides being relied on with any degree of certainty, but from such observations as have been made on the islands in the open ocean, it may be assumed that the rise and fall of the tide does not exceed two feet. This agrees with

the theoretical variation of level as given by Sir George Airey. He has calculated that the height of the tidal wave following the moon over the open ocean is at springs 1·34 foot, due to the moon, and 0·61 foot, due to the sun, or a total elevation of the water of 1·95 foot. At neaps the negative influence of the sun, he calculated, diminished that due to the moon 0·61 foot, making the rise 0·73 foot; the rise of spring tides being thus theoretically as 1·95 to 0·73 foot. This will be found to accord generally with the actual facts.

The tidal waves which affect all the waters of the earth may be divided into five classes:—

1. The great primary wave of the Southern Ocean, which is directly due to the influence of the sun and moon. This wave does not undulate in the ordinary sense of the word, for its crest always moves forward in one direction. Its rise and fall may be taken as two feet at spring tides, and nine inches at neaps.

2. The ocean tidal wave, propagated from this primary wave into the Atlantic and the Pacific, receiving its impulse from it, and which undulates alternately backwards and forwards as the crest or the trough of the primary wave passes the points of connection. Its line of direction is at right angles to the course of the tide-producing agents, and to that of the primary wave. In the open part of the ocean the rise and fall of this wave is the same as that from which it is generated.

3. The coast tide. This is derived from that of the ocean, but altered in character owing to its motion being checked by coming in contact with the coast, and thus becomes raised above the normal level by the momentum of the wave. The height of this tide varies at every different part of the coast.

4. The estuary tide. This is derived from the ocean tide, but also varies in the height which it rises and falls, due to the contour and depth of the estuary. The momentum in extreme cases raises the water to a height of twenty or thirty times as great as the ocean tide.

5. The river tide. This generally partakes of the character of both a tide and a current. The tide is propagated up the river, when the water is of sufficient depth, at a much greater rate than that at which the tidal current runs up the channel. When the depth is not sufficient to allow of the free entrance of the tide, the result is only a tidal current, the velocity of which

sometimes is great, and occasionally results in the creation of a bore.

Although we have no direct observations confirming the fact, tides must be generated both in the Pacific and Atlantic. The conditions in these oceans are not favourable to the formation of a free tide wave, and only a single tide can be generated in twenty-four hours. The wave raised in the Atlantic when the moon reaches the east side of the ocean, and progressing with her to the west side, is stopped there by the land on the coast of America, whence it is reflected back, and so undulates backwards and forwards, and assists in its own destruction. Taking the distance as three thousand miles, it would take four and a half hours for such a wave to cross. It is, however, also met and absorbed by the tide coming from the Southern Ocean, increasing its elevation. The tides generally north of a line drawn across the Atlantic appear to be higher than those on the south, so that some such effect as that here described probably does take place.

In the Mediterranean, which has the same direction as the transit of the moon, there is an undulation and tidal rise and fall varying from six inches to a foot and a half, which cannot be accounted for by the volume of water which passes through the Straits of Gibraltar. In the inland seas, such as the Caspian, the Black Sea, and the Baltic, there is no doubt a rise and fall due to the action of the sun and moon, but the moon's transit across these seas is too rapid to allow of the generation of an appreciable wave. Close observation has, however, detected a rise and fall of about three inches on one of the inland lakes of America coincident with the transit of the moon.

To fully realize the action of the tidal wave in its progress from the Southern Ocean to these shores, it is desirable to have a clear idea of the phenomenon of the ordinary oscillating waves of the ocean, and what Mr. Scott Russell has denominated the great primary tidal wave.

In a wave of oscillation, the moving forward, or travel of the particles, is more apparent than real. The crest and trough change places, and so the form moves, but the particles of water do not travel beyond the length of the wave, or from crest to crest and trough to trough. This will be seen from the diagram in Fig. 9.

Let A, B, C represent the surface of the water, A and C being

the two crests of the tide wave, and *a, c* the two troughs, the motion being in the direction shown by the arrow. *a, b, c* represents the altered position of the wave after an undulation. To effect this change of position, the water at A has sunk to *a*,

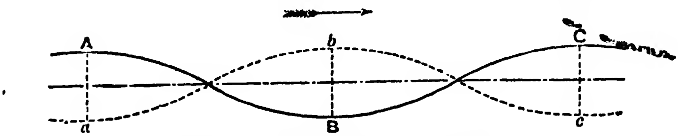

FIG. 9.—Diagram showing motion of waves.

and that at B risen to *b*. It will thus be seen that the advance of the wave is produced without any advance of the water, but by its particles rising and sinking alternately in a vertical direction. This may be further illustrated by a chain of sufficient length, fixed at both ends, to which a rapid up and down motion is imparted at one end; this follows in a series of waves along the chain, but neither the individual links nor the chain makes any advance.

The tidal wave, on the other hand, is described by Mr. Scott Russell "as differing from every other species of wave in the motion which is given to the individual particles of the fluid through which the wave is propagated. By the transit of the wave the particles of fluid are raised from their places, transferred forwards in the direction of the motion of the wave, and permanently deposited at rest in a new place at a considerable distance from the original position. There is no retrogradation, no oscillation; the motion is all in the same direction, and the extent of the transference is equal throughout the whole depth. Hence this wave may be descriptively designated as the great primary wave of translation. The motion of translation commences when the anterior surface of the wave is vertically over a given series of particles; it increases in velocity until the crest of the wave has come to be vertically over them, and from this moment translation is retarded, and the particles are left in a condition of perfect rest, at the instant when the posterior surface of the wave has terminated its transit through the vertical plane in which they lie."

In wind waves there is a partial displacement on the surface, which only extends to a few feet below it, the distance from crest to crest being comparatively short. The action of an oscillating wave on a floating substance is to depress it vertically

and raise it again without any forward motion. The tide wave carries the substance along with it over a certain distance, this distance being, however, only a very small portion of that over which the crest of the tidal wave travels. A vessel going in the same direction as the flood tide is thus expedited in her progress, and if going against the tide is retarded.

There are thus in the ocean two waves, one the long undulation of the tide reaching from the surface to the bottom, and the other the oscillations caused by the wind on the surface of the tidal wave. If the wind is acting in the same direction as the motion of the tide, the crests of the oscillations are further apart and the motion more gentle than when it is blowing in a contrary direction to the tidal motion, the oscillation in the latter case being shorter and more broken.

A tidal wave must not, however, be confounded with a tidal current. For example, in the North Sea the tidal wave is propagated at the rate of fifty to sixty miles an hour, whereas the run of the tide is not greater than at the rate of two knots. In the Thames the tidal wave advances up the river at the rate of over thirty miles an hour, whereas the tidal current is not more than about two miles an hour.

A tidal wave may travel in the opposite direction to that in which a current is moving. An example of this is found in the Gulf Stream, which moves continually in a north-easterly direction along the coast of America; the tidal wave alternately progresses with it on the flood, and against it on the ebb. In a river down which a strong freshet is running, the tidal wave will be propagated up the channel, raising the surface while the current still continues to run down.

Tides in Estuaries.—The tides in estuaries are propagated from the great tide wave of the ocean. As the undulation of the tidal wave of the ocean passes the mouth of a river, the part nearest the coast is deflected from its course and flows into the channel, its course being influenced by the contour of the coastline and the projections which are most prominent on the near or far side of the mouth. The branch wave does not diffuse itself equally in all directions, but the main set of the tidal wave in the estuary is in a direction the axis of which is along the line of the deepest soundings. The set of the tide is from this line towards the shore. If the shores converge, the area for the reception of the wave is diminished and its velocity is reduced;

the momentum which the water has acquired from the ocean tide wave being expended in lifting the water or heaping it up. As the wave advances and its momentum is absorbed by this process, and also in overcoming the momentum of the river-water coming in an opposite direction, and the friction along the channel, its height gradually diminishes, until the effect is exhausted and destroyed.

Effect of Atmospheric Pressure.—There are occasional disturbing causes which cannot be calculated, and which cause the tides to rise higher or fall lower than the calculated heights given in the Tide Tables. The pressure of the atmosphere on the surface of the ocean has a material effect on the height, the surface of the water varying inversely as the mercury in the barometer. As the pressure of the atmosphere is decreased and the mercury rises the water in the ocean is depressed. Mr. Lubbock, in his investigations into the tides of the Thames, found that a rise of one inch in the barometer caused a depression in the height of high water amounting to 7 inches in London, 11 inches at Liverpool, and 13½ at Bristol, the difference being about in proportion to the greater rise of tide at each port. A sudden fall in the barometer, on the other hand, leads to an increase in the height of the tide. In the French *Annuaire des Marées* a table is given of deductions to be made from the calculated height of the tide in each centimetre of rise in the mercury, from 30·00 to 30·70 inches, the total allowance for the 0·70 inch rise being 10½ inches. No calculation is given for any other height of the barometer. It may be assumed that approximately a variation in the height of the barometer of one inch makes a difference of 0·35 inch for every foot the tide rises at any particular place.

Effect of the Wind.—The force and direction of the wind also have a material influence both on the height of the high and low water in a river. The amount of effect on the tides of any particular port will depend on its situation and exposure. The wind blowing on any large sheet of water alters the level of the surface, depressing it on the windward side, and raising it on the lee side. Where winds prevail from the same direction for long periods they are the cause of a continual current in one direction, a phenomena that is often to be met with in inland seas, and which has a material bearing in the direction which should be given to piers carried out for the purpose of deepening the channels of the rivers which discharge into these seas. The

author has found that a strong wind has the effect of altering the level of the water in an inland lake about half a mile across as much as 9 inches between the windward and the lee side. In a large inland sea, the effect of the wind has to be taken into consideration in the navigation and berthing of vessels, a shift in the wind having the same effect as a tide, and causing either deep or shoal water. Thus in the Caspian the wind raises or depresses the water 6 feet, according to its direction, making a total variation of 12 feet. A signal-boat is stationed at the roadstead at the mouth of the Volga, to indicate to mariners the depth of water available. On the coast of Holland in the North Sea, heavy gales sometimes raise the tide at Ymuiden from its normal height of 3 feet to 10 feet.

Gales which have their direction the same as that of the main set of the flood stream cause high water to be raised above its normal or calculated height, and those which have their direction the same as the main set of the ebb stream depress the low water to an equal extent. Thus on the West Coast in the Irish sea, a south-west gale causes a high tide in the Mersey and the Ribble estuaries, and when from the opposite direction a low ebb. On the East Coast gales from the north-east to north-west, especially when accompanied by a low barometer, raise the tides from Pentland Firth to the Thames from 2 to 3 feet, and cause them to flow half an hour earlier. South-east to south-west winds produce the opposite effect. The effect of such gales extends to the English Channel, and is felt as low down as Dungeness.

The difference in height depends on the force and continuance of the gale. A rough approximation may be taken that a strong gale will raise the high-water level as many inches above its calculated height, as given in the Tide Tables, as the tide rises in feet. Thus a tide given as rising 20 feet above low water would be increased to 21 feet 8 inches.

The conjunction of the following circumstances would result in an extreme high tide: A spring tide at the time of the equinox with the moon in perigee; a strong gale blowing continuously in the same direction as the flowing tide in the open sea and suddenly changing to an on-shore wind on the rising tide; and a sudden depression in the barometer occurring at the same period.

Five times during the present century the winds have caused the tides in the Wash to rise more than 4 feet above the

ordinary level of spring tides. In the Thames the difference between two successive tides has amounted to as much as 7 feet 5 inches, the average variation of twenty-two successive tides following gales being about 5 feet. The rise above Trinity standard at periods varying from two to five years has been from 3½ to 4¼ feet; neap tides also being raised as much as 4 feet 4 inches above the calculated height. The highest known tide in the Thames was that of January, 1877, which rose 4 feet 3 inches above Trinity standard and 3 feet 4 inches above the calculated rise. Taking four tides, which rose from 3 feet 9 inches to 4 feet 3 inches above Trinity standard, and allowing 22 feet as the range of the tide, this would give 1½ inch extra rise for every foot of range. At Liverpool, when the range of a spring tide is about 27 feet, strong gales make a difference in the height of spring tides of 5 feet.

The wind also considerably affects the level of low water, depressing this in strong gales blowing in the direction of the ebb current. On the coast of Holland strong winds from the south-east have caused two extraordinarily low consecutive ebbs to follow one another with a very slight rise between, even this remaining below mean low-water level. In the La Plata heavy gales from the north-east to north-west cause the water to rise above its ordinary level 8 feet and to fall 4 feet below, making a difference of 12 feet in the level of low water.

After heavy gales it occasionally happens that the tide in a river, after attaining its height and having commenced to ebb for some time, will flow again and rise higher on the second flow than at the first.

High tides are always accompanied by low ebbs, the water heaped up in one place being drawn away from another.

Tidal Peculiarities.—The tides around the coast in many places depart from the regularity which occurs in the open ocean; thus in the English Channel the tidal wave setting into the Bay of St. Malo causes the water to rise at springs at Brehut 39 feet, and at neaps at 23½ feet. At St. Malo the rise is as much as 44½ feet at high spring tides. Round Guernsey tide and half tide prevail, and generally round the Channel Islands the tidal stream changes its direction by a rotary motion from east by north to west and south, making a complete circuit of the compass in a little over 12 hours. The current is also

extremely rapid in places, increasing about 3 knots in the offing off Guernsey to 4½ near the island and over 7 between the islands.

In the Bay of Calvados there is a long period of slack at high water. At Havre the slack of high water lasts practically 3½ hours. Actual slack lasts for an hour; for the next hour the level only varies from 3 to 4 inches. During 3 hours the tide only rises and falls 13 inches. Thus spring tides, which rise 23 feet, flow for 3½ hours, remain almost stationary 2½ hours, and ebb 6½ hours. At Honfleur the time of slack water lasts from 15 to 20 minutes, but the variation in level from half an hour before to half an hour after high water is only from 3 to 4 inches. This period of still water is caused by a second tidal wave following on the first, which bends into the bay and, striking the Cotentin peninsula, travels afterwards along the coast of Calvados, and reaches Havre later than the tide which has already come from the other direction. There is also a long interval of slack at low water in front of Havre. The difference in the rise between springs and neaps is also abnormal, the latter rising 9·84 feet, and the former 23 feet.

On the north side of the English Channel, in Poole Harbour, the tide stands nearly at the level of high water for about 3½ hours, there being two periods of high water here, the second being 3½ hours after the first. The tides at this part of the Channel present a great contrast to those in the Bay of St. Malo, springs only rising 6½ feet, and neaps 4¾ feet. At Christchurch, Swanage, and Southampton there are also two high waters, the first high water being 2½ hours before the second at Christchurch, 4 hours at Swanage, and 2 hours at Southampton. The Isle of Wight being situated across the entrance to Southampton Water, a portion of the great tidal wave, in its progress up the Channel, becomes separated from the main body, and, flowing up the Needles passage into the Solent, reaches Southampton, and causes the first tide about the same time that the main body arrives at Dunnose Point. This tide, beginning to ebb, is stopped and driven back again by the main stream from Spithead. After low water the tide rises steadily for 7 hours, which causes the first high water; it then ebbs for an hour 9 inches, and then commences to rise again. In 1½ hour it reaches about 6 inches higher than its former level; this is the second high water. The influence of this second tide

extends as far as Portland, but westward of St. Alban's Head it comes so near the time of low water and causes so small a rise that it is called the second low water, the intermediate rise being called the gulder. At Lulworth the first low water takes place $4\frac{1}{2}$ hours after high water; the gulder then rises for $1\frac{1}{2}$ hour from 5 to 7 inches, and the second low water occurs 2 hours after the gulder has ceased rising. At Weymouth the time of first and second low water is nearly the same as at Lulworth, the rise of the gulder being somewhat greater. At Portland Breakwater the first low water is 5 hours after high water, and the second 3 hours later. At the Nab Rock, where the tidal stream through Spithead and round Dunnose meet, the tides are rotary, the first of flood setting east and going north-west a little before high water, the ebb setting westward and round by south to the east. There is also another peculiarity about the tides in this part of the Channel, the flood tide at Chichester, Langston, Southampton, and Portsmouth, and the other harbours in the Solent, lasting about 2 hours longer than the ebb, the flood continuing 7 hours, and the ebb 5 hours only. This is occasioned by the second flood stream coming round the east of the Isle of Wight and joining that from the west. After this accession the rise of the tide becomes more rapid, which accelerates the filling of the harbours and prolongs the natural duration of the flood.

In the Bristol Channel the variation in the level of the tide is very abnormal. At the entrance between Bude Haven and Pembroke the rise of ordinary spring tides is 23 feet. Where the channel terminates and the Severn commences, about the mouth of the river Avon, the rise is 40 feet; owing to the shoaling and contraction of the waterway the tide then falls off, the rise at Gloucester being only $5\frac{1}{2}$ feet. The tides running out of the Severn up the Wye are the highest in this country. The water is so gorged up this river that exceptionally high tides rise above low water of spring tides at Chepstow Bridge 50 feet, the maximum recorded distance between extreme low and extreme high water being 53 feet. The actual rise above the mean level of the sea is about $23\frac{1}{2}$ feet for an ordinary spring tide, and $29\frac{3}{4}$ feet for an extraordinary tide; so that the extreme variation is due partly to the heaping up of the water and partly to the water being drawn out, the trough of the tidal wave descending nearly as much below the mean level of the

sea as the crest rises above it. In 1839, a committee of the British Association had a series of levels run from Portishead in the Bristol Channel to Axmouth in the English Channel, and also a series of observations of the tides taken at each of these places, in order to determine the difference of level of the surface of the water at tide time at the two places. The result showed that, with a mean tide rising 35½ feet at Portishead and 10 feet at Axmouth, the mean level of the sea was only 9 inches higher at the former place than at the latter. The high-water level rose 13·6 feet higher at Portishead than at Axmouth, and the low water fell 12·14 lower, making the total difference in the level of high and low water of 25·74 feet.

In St. George's Channel leading to the Irish Sea the tide sets from the south-west towards the west coast of Wales, and while the tidal wave rises from 14 to 15 feet in Cardigan Bay, the rise on the coast of Ireland on the opposite side is only from 3½ to 4 feet. In the Irish Sea the tide sets directly towards Liverpool Bay both from the north and from the south, causing a gorging up. While at Holyhead the rise is only 16 feet, in Liverpool Bay it is 27½ feet; on the opposite Irish coast the rise is only from 12 to 13 feet. South of the Isle of Man, although the rise of the tide is 18 feet, there is an area of perpetual slack water; while between the Tuskars and Arklow, although there is a rise in one part of only from 1 to 2 feet, there is a strong tidal current.

The most disturbed condition of the tides round the coast of the British Islands is on the north of Scotland, between the mainland and the islands of Shetland and Orkney. Owing to the opposition caused to the tidal wave from the Atlantic, the velocity and turbulence of the tidal stream is so great in Pentland Firth that when strong gales prevail at spring tides the sea is not navigable. On some parts of the shores of the Orkneys the breakers rise to a height of 60 feet, and the tidal current runs through the firth with a velocity of 7 to 8 knots, and in one place reaches nearly 11 knots. Between one side of Sanday and the other, the distance being only half a mile, the difference in level of the sea is nearly 5 feet, and high water is 1¾ hour later on the east than on the west side. The effect of the tidal wave on the whole mass of water and throughout its whole depth is evidenced by the fact that the position of shoal ridges at depths of 30 to 47 fathoms is indicated in calm weather by

ripples on the surface, and when the stream is only moving at the rate of a knot.

On the East Coast, the tide setting into Lynn Well affords an illustration of what is known as "tide and half tide." The flood running up Lynn Well strikes the head of the bay, and at about the time of half flood is split into two parts, one current continuing south-east along the centre of the Well, and up the rivers Ouse and Nene, and the other running in the opposite direction, and to the east along the Norfolk coast, the tidal stream thus running in opposite directions at the same time.

In the North Sea off the Wash, the tides have in places a rotary motion. Outside the Dowsing and Docking shoals the tide never slackens, the first quarter flood running from north-west, the second quarter from north-east, last half of the flood and the first quarter of ebb from east to south-south-east; half ebb to low water, from south-west to west-north-west, the strength continuing about $2\frac{1}{2}$ to 3 knots. At the Dudgeon shoal the tidal stream also never slackens, making a complete circuit of the compass in 12 hours. Between Cromer and Winterton the tidal wave is much retarded, taking $1\frac{1}{2}$ hour to travel a distance of 25 miles, and the rise and fall decreasing from about 15 feet at Cromer to 8 feet at Winterton Ness, and 5 feet at Yarmouth. There is also a rotary action near Winterton and Hasborough, but in the opposite direction to that at the Dowsing and Dudgeon, the set here being from east to west. Off Yarmouth the level of the sea varies less than 6 inches from about an hour after both high and low water. The winds here have a great effect on the tide, strong north-west gales raising the water 7 feet above the rise of an ordinary spring tide, and sudden changes in the direction of the wind making a difference of from 3 to 4 feet in the level of high water of succeeding tides. At the Ower lightship, between Cromer and Yarmouth, there is no sensible rising of the tide until 3 hours after low water; when the ebb stream is nearly done a sudden rise of from 5 to 6 feet occurs, so that nearly the whole rise of 9 feet at spring tides occurs in the last 3 hours. At the Lemon and Ower, also at Smith's Knoll, and at the Galloper light-vessel off the Kentish Knock, and near the Swin at the mouth of the Thames, the tides take a rotary direction, moving from west to east.

The places where the lowest tides occur in the sea surrounding this coast are termed the *nodes*. In the English Channel the

nodal line passes from Swanage, where the rise is only 6½ feet, to Barfleur on the French Coast, where the rise is 17 feet; the rise on the west side of this place being 37 feet, and on the east 22 feet. In the North Sea the nodal line extends from Yarmouth, where the rise is 6 feet, to Nieuwediep, on the Dutch coast, where the rise is 4 feet. In the Irish Sea the line extends from Courtown, where the rise is 3¾ feet, to Cardigan Bay, where the rise is 12 feet, this line being about the same distance from the entrance to the Irish Sea, or a line drawn from Cape Clear to the Land's End, as Swanage is from the entrance to the English Channel. These places are also all about the same distance, 150 miles, from the head of the tide at Lynn Well, Beachy Head, and St. David's Head, respectively, and high water at full and change occurs at each place at the same time. The time of high water in the Bristol Channel and in St. Malo Bay, where the tides rise the highest of anywhere round the coast, is the same; and so also the distance of the two places from the entrance to the English Channel, the line being drawn from the two projecting headlands.

At Marsdiep, on the Helder, where the average rise of tide is 5¼ feet, the tide remains at high water for 3¼ hours, the flood lasting 3¼ hours and the ebb 6 hours. At spring tides the wave shows two crests with a depression between. This is due to the meeting of the two tidal waves, one from the Channel, and the other from Scotland.

There is a very great variation in the rise and fall of the tide on the coasts of the open ocean. Off Cape Horn, owing to the contraction in the waterway of the Southern Ocean, and the opposition offered to the progress of the tidal wave, the sea here is always excessively turbulent and dangerous for navigation. At Staten Island, on the southern extremity of Tierra del Fuego, and at the Falkland Islands the rise is from 5 to 8 feet, and at Port Gallegas and Santa Cruz on the coast to the north of the Straits, from 40 to 45 feet. In the Straits of Magellan, on the Pacific side, the difference between high and low water is from 36 to 44 feet. About the middle of the Straits, near Sandy Point and Cape Virgin, where they widen out very considerably, the difference is from 5 to 7 feet; it then increases again to 8 feet. On the Pacific side the difference is from 4 to 6 feet. On the coast of Central America, on the Pacific side, the rise is about 15 feet. In the Gulf of Darien and at Panama it increases to

20 and 24 feet; on the opposite coast of the Isthmus, on the Atlantic side, the rise is only from 1½ to 2 feet.

In the Bay of Fundy, on the north-east coast of America, there is a very great difference between the level of low and high water, amounting to about 40 feet at spring tides, and in extreme cases even as much as 60 feet, the rise in the open ocean being from 5 to 6 feet. Mr. M. Murphy, the Government engineer of Nova Scotia, says, in a paper contributed to the Nova Scotia Institute of Natural Science in 1867, that it is an error to state that the tides in the Bay of Fundy rise 50 or 60 feet above the mean low-water level of the sea, as the tidal wave on its retreat scoops back with it nearly as much water in depth below the mean level as it carries with it in its advance above the level. The tides seldom rise to a greater height above the mean level than 22 feet, but as the low water falls out to the same distance below the mean level it is correct to say that between the highest and lowest water there is a difference of from 50 to 60 feet at extreme springs.

Amongst the West India Islands and in the Gulf of Mexico the tidal rise is only from 1½ to 2 feet, whereas in the Pacific, across the narrow neck of land which divides the two seas, the rise is from 12 to 18 feet. Between Cape St. George and Cape Florida there are two tides during the day subject to a large diurnal inequality, and the rise here is nearly double that in the other parts of the gulf. In the Gulf of Mexico there is only one tide in the day, the rise and fall increasing or decreasing with the moon's declination. This may probably be due to the fact that the flood tide, being driven into the Gulf by the momentum of the ocean wave, and having a long run up the Mississippi and other large rivers which are connected with the Gulf, pours so great a quantity of water into the Gulf that the ebb has not time to get out again before it is met by the succeeding flood, and consequently only every alternate wave reaches the head of the bay. In the same way, in some rivers into which the tide enters with a great head and has a long run, the low water of spring tides does not ebb out as low as that of neaps.

At Singapore, where there is a rise of 10 feet at spring tides, there is a very large diurnal inequality, amounting at times to 6 feet, the low water being affected to the same extent.

At Lucipara, in the Banks Strait, where there is a rise of 10 feet at spring tides, there is only one tide in the day, and this

very irregular. So also at Bawean, in the Java Sea, with a rise of about 10 feet there is only one tide in the day, and this occurs in the morning from April to October, and in the evening for the rest of the year.

At Whampoa, in the China Sea, in May and June the level of spring tides is 4 feet, and of neaps 2 feet higher than at the equinox. At Sydney, in Australia, the night tides during June and July are at times nearly 2 feet higher than the day tides, and the reverse is the case in December and January.

Progress of the Tidal Wave.—In order to trace with any degree of accuracy the progress of the tidal wave from the Southern Ocean, through the Atlantic, to the coasts of this country it would be necessary to institute simultaneous observations along the whole of its course. No such observations, however, having been made, the only course that can be adopted is to take the time of high water at full and change, as recorded in the Tide Tables and Admiralty Sailing Directions at the various places along the coast. This only gives an approximate result, as, owing to the effect of projections and indentations in the coast-line diverting the course of the tidal current, and other disturbing causes, the time and height of the tides along the coast is very irregular and difficult to follow. The tidal current appears in many cases to assume a rotary motion, being reflected from a projecting part of the coast, and returning back along the shore, making the time of high water later at a place several miles south. Even at the islands in the open ocean high water is in many places several hours later on one side of the island than on the other, and the tides vary considerably in their rise and fall.

Taking the tide which makes high water at full and change in the Southern Ocean on the meridian of Greenwich at noon, it is also high water on the opposite side of the globe, at the islands off the southern coast of New Zealand, and low water at the islands to the east, about midway between these points. Owing to the disturbance caused by the narrow strait between Tierra del Fuego and Graham's Land, the time of low water is not so well defined on the west side; but, as nearly as can be ascertained, low water on the meridian of 80°, or half-way between the two high waters, is at the same time as high water on the meridian of Greenwich.

In the chart, Fig. 10, the upper figures represent the local

time of high-water spring tides, and the lower the rise in feet above low water. The arrows show the direction of the flood tide. As, in order to trace the time the tidal wave takes to advance, it is necessary to use the same standard of time at each place on the chart, Greenwich time is given as well as local time, the former being distinguished by being enclosed in a circle.

In the centre of the Atlantic is a high ridge which runs from the Southern Ocean, and continues through the narrow neck between the projecting promontories of South America and Africa, and thence along the open space between the West India Islands and the coast of Africa through the North Atlantic up to the Arctic Seas. This ridge is of varying width, and is elevated about 1500 fathoms above the bottom, decreasing the depth of the water where it runs about one-half. This elevation must have a material effect in guiding the direction of the tidal current.

The coast tidal wave reaches off the south of Africa about 1½ hour after leaving the Southern Ocean; and the part which projects westward from Fernando Po, which is nearly on the equator, in 4½ hours, or at the rate of 660 nautical miles an hour, the depth being about 15,000 feet. From here the progress of the wave is delayed, having to force its way through the narrow gorge caused by the projection of the two mainlands and the elevation of the ridge in the centre of the channel. It does not reach latitude 20° north, off the north-west coast of Africa, till noon, or at the rate of 160 miles an hour. From here the progress is more rapid, the wave reaching off the southern part of these Islands in latitude 50° at 4.30, being at the rate of 400 miles an hour, the depth here also being about 15,000 feet. The wave on the west side of the South Atlantic also receives a check on reaching the narrow gorge off Cape St. Roque, and appears to be deflected back, moving southwards along the coast, the tide on this side being much later on the same latitude than on the African coast. The time of high water off Cape St. Roque is about six o'clock, as against half-past four off Cape Palmas on the opposite side.

The progress of the wave along the north coast of South America and past the West India Islands is disturbed by the sudden opening out of the width, resulting in the eddy and the dead water of the Sargossa Sea, and the shoaling in the depth

caused by a branch of the central ridge extending to the mainland. The smallness of the sectional area of the Channel also restricts the quantity of water passing through, and, the main set following the deep channel northwards, the quantity passing in amongst the West India Islands and into the Carribean Sea and Gulf of Mexico is only sufficient to raise a tide of 1 foot 6 inches. Owing also to the hindrance in passing through the gorge off Cape St. Roque, high water, which takes place at noon off Cape Blanco, on the African Coast, does not attain at the same time till past the Bermudas, or in about latitude 40°, 1200 miles further. From here the tide wave appears to take its main set between the east coast of North America and the Dolphin Ridge, one branch following the same course as the Gulf Stream, and setting across to the north coast of Scotland, another branch going up Baffin Bay, another the east side of Greenland, and another along the coast of Norway, meeting the tidal current of the Arctic Ocean coming from the east from New Siberia and Francis Joseph Land.

The crest of the tidal wave, which attains its height at full and change at the Scilly Islands at 4.30, reaches the north of Scotland off Cape Wrath at 7.30, a distance of 500 miles, or at the rate of 166 miles an hour, the average depth of the low-water soundings off the coast being about 400 fathoms. It takes 2¼ hours from Cape Wrath to the Shetland Islands, and it reaches Flamborough on the east coast 12 hours after leaving Scilly, a distance from the Shetlands of 360 miles, having travelled down the North Sea at the rate of about 55 miles an hour, the depth averaging about 40 fathoms. Seven hours later, or about 11.30, it has reached the Thames estuary, 19 hours later than at Scilly, the progress from Flamborough to the Thames being at the rate of 21½ miles an hour, the depth varying from 15 to 20 fathoms. The course of the tidal wave is obstructed in this part of its course by several submerged sandbanks. The North Sea is practically a large bay. While, therefore, one branch of the tide continues along the English coast to the Straits of Dover and meets the tide from the English Channel, the main body of the water sweeps round at the south end of the bay to the east and north along the coast of Holland and Germany, and, after throwing off a branch into the Baltic, meets the set coming from the north off the south end of the coast of Norway. The rise here is only about 4 feet, gradually dying off to nothing in the Baltic.

The crest of the tide, which passes Scilly at 4.30 and travels up the English Channel, reaches the east end of the Straits of Dover 7 hours later, or at about 11.30, the crest of the two tides thus reaching this point about the same time. The distance is 300 miles, and the rate of progress along the channel at the rate of 43 miles an hour. The low-water soundings gradually diminish eastwards from 50 to 20 fathoms. When it is low water at the head of the tide, say between Beachy Head and Dover in the English Channel, or the Isle of Man in the Irish Sea, it is high water in the parts where the tide is about 6 hours previously. There is, therefore, a slope of the water on both sides towards the place of the head of the tide, in consequence of which the tides commence to flow from both sides towards the same place. After flowing a certain time, the currents attain their greatest velocity at the moment when the surface of the water is at its mean level and all slope is destroyed, yet the currents continue to flow by virtue of their acquired momentum, and run uphill for the last part of the tide, until the water has acquired an equal slope in the opposite direction, when the process is reversed. In the Irish Sea, the slope at its maximum is 2·65 inches per mile, and in the English Channel an inch in a mile.

The maximum rate of the stream is at half-tide, when the surface has the least depression, and the stream ceases when the greatest elevation and depression are attained.

Rise of Tide.—In the South Atlantic, at Ascension and St. Helena, the rise of spring tides is only from 2 to 3 feet, and at the West India Islands from 1½ to 2 feet. At Tahiti, in the South Pacific, the rise is 1½ foot. The height of the tide in the open ocean can only be approximately ascertained from the height at the islands in its midst. The heights at these places may, however, be affected by the tidal wave being checked by the coast or by winds. It may be taken that the crest of the free tide-wave of the ocean does not reach more than about 2 feet. As the wave advances, and its momentum is checked by the shores of the mainland, this height is increased to 6 and 8 feet under ordinary conditions, and to ten times this height under exceptional circumstances. Along the coast of South America and the west coast of Africa the rise of spring tides is from 6 to 8 feet. When the ocean widens out on the north of South America, the rise is only about 2 feet at the West India Islands, and about

1½ in the Gulf of Mexico. Along the west coast of Europe the rise is from 12 to 16 feet, and on the east coast of the United States, from 6 to 8 feet. At the Scilly Islands the rise is 16 feet; at Cape Clear, on the south part of Ireland, 9 feet; and varying along the west coast from 9 to 13 feet. At the Mull of Cantire the rise is 4 feet; at Tobermory, Isle of Mull, and Iona, and to Stornoway, the rise is from 8 to 9 feet; and 15½ feet at Cape Wrath. Off the Orkneys the rise is 10 feet, and off the Shetlands 6 feet. Down the east coast the rise is from 10 to 12 feet, increasing to 15 feet from Eyemouth down the east coast of England to Bridlington. Off the Humber it rises to 19 feet, and to 22 feet in the Wash; at Yarmouth it has fallen to 6 feet, which corresponds with the rise on the opposite coast of Holland. At Harwich it increases again to 9 feet, and to 13 feet at Margate and in the Thames estuary. In the Straits of Dover, the rise is 15 feet on the north side at Dover, and 17 feet on the south at Calais. Here the north tide meets the branch which sets up the English Channel. This wave, after leaving the Scilly Islands with a rise of 16 feet, falls off to 9 feet at Portland Bill, and 7½ at the Needles on the west of the Isle of Wight. It then increases again to 16 feet at Selsea Bill, 19 feet at Brighton, 20 at Beachy Head, and 24 feet at Hastings.

The tide sets into the Irish Sea both from the south through St. George's Channel and on the north between the coasts of Ireland and Scotland, through the North Channel. The two tides meet in Morecambe Bay. The main stream from the south sets towards the Isle of Man, where the rise is 16 feet, which it passes to the east. The eastern stream sweeps round the north-west of Anglesea with a rise of 16 feet towards Liverpool and Morecambe Bays, when it is met by the northern tide, causing a rise of from 27 to 28 feet. The western stream runs along the Irish coast, the rise at Carnsore Point being 9 feet, to Wicklow Head, and expends itself in a large area of still water between the Isle of Man and Carlingford. Between Wexford and Wicklow Head the tidal currents meet and destroy each other, the rise and fall being only 3½ feet at Courtown, and there is still water at all times, and no perceptible current.

In the North Channel the tides fall off from 14 feet off Lough Strangford to 7 at Lough Earne, and from 3 to 4 feet in the narrow channel between the Mull of Cantire on the Scotch Coast and Fair Head on the Irish side, increasing to 6½

feet at Portrush, and 12 at Lough Swilly on the north of Ireland.

At the Faroe Islands the rise is $6\frac{1}{2}$ feet; at Spitzbergen, $3\frac{1}{2}$ feet; at Hammerfest, 9 feet; at Nova Zembla, 10 feet; in the White Sea it varies from 2 to 20 feet. In the North Sea, at Heligoland, there is a rise of 9 feet, increasing to 11 feet at the entrance to the Elbe. From this the tide gradually dies out in the Baltic, the narrow entrance of the Kattegat not affording a channel of sufficient capacity for the tidal wave to enter freely. On the east shore of the North Sea the rise varies from 4 feet off the Norwegian and Dutch coasts to 16 feet off the coast of Belgium.

The rise and fall of the tide is not spread equally over the time occupied. There is a period of slack water both at low and high water, the length occupied by the slack varying in different situations. This is due to the time occupied in the reversal of the direction of the water. In rivers the slack of high water varies from a few minutes to half an hour. The rate of rise increases continually from slack to half-flood, when it attains its maximum, and then falls off till high water.

If the rise of the tide at any place, either at springs or neaps, be multiplied by the following constants, it will give approximately the hourly rise and fall of the water at flood and ebb:—

Hours.	Flood. Feet.	Ebb. Feet.
1	0·07	0·08
2	0·17	0·18
3	0·26	0·22
4	0·26	0·22
5	0·17	0·15
6	0·07	0·12
—	—	0·03

The ebb lasting a little longer than the flood. For example, the rise of a spring tide in an estuary is 27 feet. From the third to the fourth hour the rise will be $27 \times 0·26 = 7·02$ feet. An ebb ranging 13 feet, or falling that distance from the level of high to low water, from the fourth to the fifth hour would fall $13 \times 0·15 = 1·95$ feet.

Spring and Neap Tides.—The difference of rise between spring and neap tides varies in proportion to the range of the tides. Along the coasts of this country it varies from about 9 feet in the Bristol Channel, and 7 feet on the east side of Liverpool Bay, to

about 2 feet in the middle of the English Channel near Portland, and $2\frac{1}{2}$ feet at the upper end. Up the east coast it varies from $1\frac{1}{2}$ foot off Yarmouth to $6\frac{1}{2}$ feet in Lynn Deeps, 4 feet off Flamborough, and $2\frac{1}{2}$ feet on the east coast of Scotland. As an average it may be taken that the rise of neap tides above low water of spring tides is 75 per cent. of that of a spring tide.

New-moon tides are about $\frac{1}{70}$ of the total rise higher than full-moon tides; that is to say, if the rise of a spring tide is 21 feet, the new-moon tide will be 0·3 feet higher than that due to the full moon. The spring tides which occur when the moon is in perigee are also higher, the following springs being lower because the moon is then in apogee; the difference in height between two successive sets of spring tides due to this cause is about $\frac{1}{14}$ of the total rise.

When the sun is vertically over the equator and its path coincides with it, the tide-producing effect is at a maximum. At these periods, which occur at the equinoxes in the months of March and September, the new and full moon has also most influence, and the tides produced are at a maximum.

These heights are still further increased if the moon is in perigee at the time of her passing the meridian at the equinoxes.

In June, when the sun is furthest from the equator, the rise of the tides are at a minimum.

The highest tides and lowest ebbs from normal causes, therefore, occur at the equinoxes in March and September, and the least rise and fall in June. The June tides are often locally called "Bird tides," owing to the nests of the birds on the marshes being less subject to be covered with water owing to the small rise of the tides there.

The average rise above low water of spring tides on the coasts of this country is as follows:—

	Spring Tides. Feet.	Neap Tides. Feet.	Difference. Feet.
English Channel	14·50	11·06	3·33
Bristol Channel	30·87	23·55	7·52
St. George's Channel, east	26·00	19·46	6·57
St. George's Channel, west	10·00	7·45	2·55
Ireland, west coast	11·06	8·30	2·75
Scotland, west coast	14·17	10·70	3·47
Scotland, east coast	13·27	10·45	2·82
England, north-east coast	15·11	11·69	3·46
England, central coast	20·83	15·91	4·91
England, south-east coast	7·95	6·40	1·51
Mean ...	16·37	12·47	3·88

The Age of the Tide.—The time at which a port on the coast or a river is immediately affected by the tide is not coincident with its generation by the action of the tide-producing agents, but is so much later as the place is more distantly removed from the source of origin.

The highest spring tides in any fortnight are not, therefore, coincident with the time at which new or full moon crosses the meridian of that part, but are as many tides after as the tide is old when arriving there. Thus the tide which reaches the mouth of the English Channel is $16\frac{1}{2}$ hours old, and the tide which reaches the mouth of the Thames is $1\frac{1}{2}$ days old, having taken this time to travel from the source of its generation.

The Establishment of a Port.—The tides in this country not being directly due to the position of the sun and moon, but only to the resultant of tides caused by those luminaries in a distant sea, the effect of which is disturbed by causes operating during their course, and varying at every part of the coast, it is not possible to determine by theoretical calculation alone the time at which any given tide will arrive, or the height to which it will rise at any particular port. This can only be determined by the aid of local observation. Spite, however, of all complications, the fact remains that there are two high and two low tides every day, and that the height to which they rise and fall has a certain amount of regularity, and that the time at which they occur is coincident with certain phases of the moon. If, therefore, local observations be extended over a sufficient length of time to enable the elimination of disturbances caused by wind or the pressure of the atmosphere, it becomes practicable to establish an agreement with the time and height as deduced by calculation from the position of the tide-producing agents, and to construct tide tables, giving the time and height of the tides for any port.

The time at which it is high water at a port is of far more consequence to mariners than the age of the tide. As the tide-wave travels along a coast, the time of high water at the successive ports becomes later and later in the day. Thus if it be high water at the Scilly Islands at 4.30, it is not high water at Dover till 11 hrs. 12 min., or at Holyhead till 10 hrs. 11 min.

The time of high water, therefore, rarely coincides with the moon's southing, or the time when she comes on the meridian of a place, but follows at a greater or less interval.

At Loch Long and Greenock, also at Harwich, and the

Maplin lighthouse at the mouth of the Thames, high water at full and change occurs when the moon is on the meridian. At Skye it is 6 hours later, and at the Orkneys 9 hours. In Lynn Well it is 6 hours after, thus being low water here when the moon crosses the meridian. At Yarmouth it is 9 hours later; in the English Channel at the Needles, 10 hours; while at Newhaven the moon has nearly got back to the meridian before high water has reached that port. This variation in the time of high water is expressed in terms denoting the time at which high water occurs at the particular port in question on the days of new or full moon, or, as expressed by sailors, high water at such an hour at full and change. This is marked on charts by the letters H. W. F. & C. at 0 hrs. 0 min.

This interval between the time of transit of the moon and the time of high water at full and change, is known as the "establishment" of the port, or the "vulgar establishment," because this is the common acceptation of the meaning of the term as understood by mariners. The interval, however, varies during a lunation with the relative changes in the position of the sun and moon to the earth. The time at full and change being "established" by local observation, the time of all the tides can be calculated from it. The mean of all the intervals during half a lunation is termed the "corrected establishment." These intervals between the transit of the moon, at other times than those of full and change, and the time of high water, are termed the luni-tidal intervals.

The correction for the establishment is as follows:—

Moon's transit after the sun.	Correction in minutes.
1	– 20
2	– 30
3	– 50
4	– 60
5	– 60
6	– 60
7	– 40
8	– 10
9	+ 10
10	+ 20
11	+ 10

For example, if at Sunderland high water occurs at full and change 3 hrs. 22 min. after the moon's transit, and this is the vulgar establishment of the port. Six days afterwards the

moon's transit occurs at 6 hrs. 31 min. p.m.; then the establishment wants correcting by deducting 60 minutes and giving the luni-tidal interval as 2 hrs. 22 min., and high water will occur at 8 hrs. 53 min.

River Tides.—As the channel through which the tide wave progresses contracts in depth, it gradually changes its character from a wave to a tidal current, the wave action being merged into that of the current. As the tide proceeds up a river the inclination of the ebb current is gradually reversed, until a nearly horizontal line is reached, when there occurs a period of slack water, after which the inclination is again reversed.

The gradient of the ebb current is, however, in some cases so great that, although it becomes reduced by the flowing tide, the level still remains higher than the level of high water of the tide. In this case, although there is a swelling of the water, the current is not reversed.

In any river where there is an ebb current there will always be a rise of the water before the flood overpowers the ebb and causes an upward current. The rise of the water in a river is therefore due, to a considerable extent, to the pounding back of the ebb water. During the flowing of the tide the fresh water, prevented from flowing down the river, accumulates, the upper part of the channel acting as a reservoir. The latter part of the ebb is therefore occupied in the discharge of this accumulated fresh water, and not in the return of tidal water brought up on the flood. To this cause is due the fact that the ebb in rivers lasts longer than the flood, and has a greater effect in maintaining the channel, and also that, although there is a considerable rise of tide, the water does not necessarily become salt.

In rivers the momentum of the tidal wave, when the conditions are favourable, carries the tide to a higher level in the upper reaches than at the mouth, the reflux of the wave also causing the low water to be lower than at the outfall. Thus in the Thames the level of spring tides at London, which is 46 miles from the mouth, is 2 feet 6 inches higher than at Sheerness, and the ebb is 1 foot 4 inches lower, making a difference of range of 3 feet 10 inches. In the Humber the level of high water of spring tides at Hull, 23 miles from the sea, is 2 feet higher, and low water is 13 inches lower, than at the mouth at Spurn Point. In the Scheldt, which has a tidal run of 110 miles, and the channel of which is favourably formed for

the propagation of the tidal wave, the tidal range is 2 feet 6 inches greater a little below Antwerp than at Flushing; part of the momentum is then absorbed in passing some sharp bends, so that the range falls off 4 inches at Antwerp. In the Mersey, where the wide estuary extending above Garston is suddenly contracted at Runcorn, spring tides rise there 1 foot 10 inches higher than at Liverpool, and 2 feet 3 inches higher at Warrington. In the St. Lawrence the tide rises 5 feet at the mouth, and 14 feet at Quebec.

The fact that the lowest water is not always to be found in the sea, but at a point some distance up the estuary or river, is one that requires attention from those in charge of drainage works, as the extension of an arterial drain to an outfall on the coast may not only result in a loss of depression of the low-water level, owing to the greater distance which the water has to be taken, but also to the fact that there may be a place where there is a lower outfall.

As a general rule the spring tides ebb out in rivers much lower than the neaps, the difference being in proportion to the rise of the springs; but there are many exceptions to this, especially when the spring tide rise is great, and it runs up with great velocity. In this case, the greater quantity of water poured in at springs than at neaps has not time to get out of the river again before the next tide comes. In the Severn, the Trent, the Hull, and the Nene, the low water runs out lower at neap tides than at springs.

The following table shows the variation in the level of the tides owing to local causes, the heights being reduced to ordnance datum :—

Level of High and Low Water of Spring Tides reduced to Datum 100 Feet below Ordnance Datum.

Name of river.	Place.	Low water.	High water.	
			Ordinary spring tides.	Extraordinary spring tides.
Thames	London	92·17	112·10	117·25
Ditto	Sheerness	93·50	109·60	112·50
Mersey	Liverpool	86·49	114·37	119·08
Ribble	St. Anne's	87·63	113·63	—
Severn	Chepstow	82·37	123·50	129·74
Clyde	Port Glasgow	94·25	104·50	—
Tyne	Tynemouth	93·94	107·94	—
Humber	Hull	90·92	111·67	115·91
Ditto	Spurn Point	92·00	—	114·50
Wash	Boston	91·21	113·21	117·55
Waveney	Yarmouth	98·11	104·11	—

Bores.—When the tidal wave is propagated into a shallow river where there is not room for its development, the wave will break when its height above the surface of the water becomes equal to the depth below the surface. The first wave being impeded in its course by the friction on the bottom, the succeeding wave overtakes it, and the tidal wave flows up the channel with a vertical crest or head.

This phenomenon, which is well known in some English rivers, in two or three rivers in France, in the Amazon, and some of the Indian and Chinese rivers, is known in this country by the name of *the bore*, or *eger*, the latter word being derived from the name of a Saxon river-god. In France it is called *the mascaret*, and was known by the Indians as *the pororoca*.

In the Severn there is a very strongly developed bore. Admiral Beechey, in his report made to the Admiralty in 1849, gives the average rate of the progress of the crest of the tidal wave as increasing from 3·6 miles above Portishead, to 13·6 miles below Gloucester. In high spring tides it comes up the river with a crest of from 5 to 6 feet at the sides, and $3\frac{1}{2}$ feet in the centre. When freshets were running, the rate of progress increased from 4 to 10 miles an hour. Another account states that, with an ebb current running at the rate of from 4 to 5 knots, the bore, without any warning, came up the river in two waves of from 6 to 8 feet in height, and travelled at the rate of from 6 to 7 knots.

In the Trent the bore is slightly developed at high spring tides at Burton Stather, 4 miles above its junction with the Humber, and at ordinary springs at Keadby, where it rises 3 feet almost instantly. At Gainsborough it attains its maximum height, the first wave of the flood passing up the river there with a nearly vertical crest of from 5 to 6 feet. At Torksey, the crest diminishes to about a foot, and it gradually dies out above this place, which is 34 miles from the Humber.

There is also a small bore developed on the Ouse, above the mouth of the Trent, but it does not assume the velocity or height of that on the Trent.

In Solway Firth, the first of the flood of spring tides runs up with a bore from 3 to 4 feet high, at the rate of from 8 to 10 miles an hour.

The bore disappears from rivers which are artificially deepened, and where the tidal wave is more freely propagated

by improvements. For example, on the Witham the foot of the wave at spring tides used to advance up the river with a crest of a foot in height, its progress at the mouth being impeded by having to make its way through a shallow channel over shifting sands. When a new cut was made, by which the sandbanks were avoided and the mouth carried to comparatively deep water, the bore disappeared, and the first wave came up the river nearly an hour sooner.

On the Seine, previous to the erection of the training-walls, the depth of the water in the channel below La Hode was not more than 1·16 feet. The height of the crest of the bore, as measured on a fixed gauge, was found to be 7·15 feet; the first wave was followed by five or six secondary waves, having intervals between their crests of from 5 to 7 feet. At 2¼ minutes after the arrival of the bore it stood at 5·50 feet above low water; at 11 minutes later the northern wave arrived, causing an elevation of 1·33 feet. Above Tancarville the bore sometimes attained a height of 10 feet, and travelled at a velocity of 12 miles an hour. After the completion of the training-works the bore again appeared, owing to the width of the walls being too contracted, the first wave rushing up with a great velocity, and having a crest of 5½ feet, reaching in high spring tides to 11 feet. In 1871, H.M. gunboat *Pheasant*, while at anchor off Quillebœuf, was riding to the ebb, which was running at the rate of from 4 to 5 knots, when the bore, without any previous warning, came up the river in two waves of from 6 to 8 feet high, travelling at the rate of from 6 to 7 knots. The strain on the vessel was so great that the cable was broken, and she broke adrift, but, having steam up, was got under control.

In the upper part of the Garonne, and in the Dordogne and Gironde, the spring tides advance on the first of the flood with a considerable head at the rate of from 10 to 15 miles an hour.

Bores are to be found in the Ganges, Brahma Pootra, and Indus. In the Hooghly, a branch of the Ganges, the tide is said to travel 70 miles in four hours, and to advance with a wall 5 feet high past Calcutta.

In the Bay of Fundy, from Grand Manan to Cape Chicnecto, the tidal current runs at the rate of 10 miles an hour. In the Macan river, which empties into the Cumberland basin, the bore advances up the stream at a rate which within five minutes raises the level of the water 15 feet.

In the Amazon, at the equinoxes during three days, bores of from 12 to 15 feet in height rush up the river and along the course of the stream for 200 miles from its mouth, no less than eight tide waves simultaneously advancing. As many as five bores are sometimes at once in progress (Herschell). The tide is felt in this river at Obydos, 400 miles from the mouth, and 380 miles up the Tapagos, one of the tributaries, where there is a rise and fall of 3 inches 900 miles from the Atlantic.

The most remarkable example of a bore is to be found in China, in the river Tsien-tang-Kiang, an account of which is given in the paper by Captain W. V. Moore, R.N., in vol. 99, *Min. Proc. Inst. C.E.* The range of tide in the gulf is 12 feet, at the head of the estuary 25 feet, rising to 34 feet at extreme spring tides. The navigable width of the estuary at the head is only one-sixth that at the mouth. The low-water width of the river is about a mile. In the first hour the tide rises from 10 to 12 feet. There are two branches of the bore, which join 4 miles outside the river; when these two branches join, there is a difference of level of 19 feet between the water outside the bar and that in the mouth of the river in a distance of 20 miles. Thus the flood enters with a gradient of one foot in a mile, and at a speed of 14·6 miles an hour. The bore is over a mile wide, and has a crest 8 to 12 feet high, rising on itself or river in front at an angle of from 40 to 70 degrees. The noise caused by its approach can be heard at a distance of from 14 to 15 miles, and an hour and a half before its arrival. It maintains its breadth, height, and speed for 12 or 15 miles above the mouth of the Tsien-tang. At Hang Chan, 24 miles from the mouth, the height of the tide decreases to 6 feet, and bore to 5 feet. On rare occasions it reaches as far as 30 miles above the city.

Velocity of the Tidal Wave in Rivers.—In shallow rivers the tidal wave develops a current, the particles of water being actually moved forward along the channel, and carrying any floating object with them at the same rate at which the current moves, until the cessation of the tide. In deeper water the action is compound, the tidal wave making itself felt at the different places along the river at a rate of from 10 to 20 miles in the hour, whereas the tidal current which follows it may not travel faster than from 2 to 3 miles an hour. There are so many disturbing causes in rivers that the law relating to the propagation of the tidal wave in the ocean can not always be

applied, especially where the low-water depth is shoal. Thus on the Severn above Portishead, where the low-water depth is very shallow, the foot of the tide or the first wave proceeds at the rate of over 21 miles an hour, decreasing to 9 feet where the water is deeper, this rate being greater than in the Clyde, where the low-water depth is six times as great. In the Seine, the rate of propagation in some parts of the river is upwards of 26 miles an hour, the average rate between Havre and Martot at the end of the tide being about 17 miles an hour; the rate of the head of the tide, or the difference in time of high water between Havre and Martot, being at the rate of 25 miles an hour. In the Thames, the rate of the foot of the tide varies from 34 miles an hour in the lower reach, where the low-water depth is 35 feet, to 13 miles an hour in the upper reach, where the average depth is 15 feet; the head of the tide advancing in some parts at the rate of 43 miles an hour, and at an average rate between Southend and London Bridge of 27 miles an hour. On the Clyde, the advance of the foot of the wave varies from 6 to 9 miles an hour in the different reaches of the river, the average rate between Port Glasgow and Glasgow is 10 miles an hour, the depth varying from 17 to 20 feet; the average rate of the head of the tide being 29 miles an hour.

An investigation of the tidal conditions of a great number of rivers shows that no universal law can be laid down for the rate of propagation. As a general average it may be taken that the rate for the foot of the tide is about one mile per hour for each foot of depth, with a current of from 2 to 3 miles an hour. The rate of propagation of the head of the tide approaches more nearly the law that the rate is in proportion to the square root of the depth, an average depth in several rivers giving a rate of propagation of 21 miles an hour, which is nearly the same proportion as in the sea surrounding these coasts. The following examples from a few characteristic rivers will show the irregularity which prevails in the rate of propagation :—

The Clyde. Mr. J. Deas. April, 1872.

	Miles.	Average depth in feet.		Rate of propagation of tidal wave in miles per hour.	
		L.W.	H.W.	Foot.	Head.
Port Glasgow	0·00	—	—	—	—
Garmoyle	3·68	20	31	8·80	11·00
Dunbuck	2·00	20	31	15·00	24·00
Bowling	2·43	18	29	7·29	72·90
Dalmair	2·56	18	29	6·14	7·11
Renfrew	2·56	17	28	10·00	30·00
Glasgow harbour	4·31	17	26	12·93	25·86

The Thames.

Sheerness	0·00	—	—	—	—
Erith	27·96	30	48	34	36
Deptford...	12·53	15	34	30	30
London Bridge	23·03	10	30	13½	30
Teddington	—	5	—		—

The Mersey. Mr. J. M. Rendell. June, 1844.

Formby Point	0·0	—	—	—	—
New Brighton	8·0	36	62	9·38	23·44
Liverpool	2·0	48	75	19·53	11·72
Ellesmere Port	9·0	9	—	3·77	26·37
Runcorn	6·59		—	7·81	27·90
Fidler's Ferry	4·97	2½	—	3·67	12·03
Warrington	5·19		—	4·97	7·60

The flood current between Liverpool and Ellesmere runs at the rate of 3·73 miles an hour.

The Tyne. Mr. J. M. Rendell. May, 1850.

	Miles.	Average depth in feet.		Rate of propagation of tidal wave in miles per hour.	
		L.W.	H.W.	Foot.	Head.
Tynemouth	0·00	—	—	—	—
Prior's Stone	0·50	11	25	—	2·00
Ballast Office	0·74	5	19	2·85	2·85
Howden	2·50	4	18	4·88	9·76
Bill Point	3·85	3	15	3·71	8·90
Newcastle	2·95	3	15	5·76	8·64
Elswick	2·42	2	11	3·67	9·47
Stella	3·58	1	9	3·36	—
Newburn	1·38			1·11	5·57
Tynemouth to Newburn	17·92	—	—	2·91	8·75

The Severn. Admiral Beechey. 1849.

	Miles.	Average depth in feet. L.W.	Average depth in feet. H.W.	Rate of propagation of tidal wave in miles per hour. Foot.	Rate of propagation of tidal wave in miles per hour. Head.
Lundy Island	0·00	—	—	—	—
Cardiff	70·00	80	117	—	60·0
Portishead	16·00	70	110	—	57·0
Chepstow	10·00	50	80	—	35·0
Sharpness	12·52	8	36	17·74	18 12
Newnham	7·54	3	10	21 57	—
Framilode	4·70			21 08	---
Rosemary	4·00	10	20	9·67	21·86
Stonebeach	4·48	11	18	11·73	—
How Bridge	7·58	5	10	9·67	8·47
Hythe Bridge	5·27	6	9	8·08	8·42
Upton Bridge	5·64	5	10	11·74	18·80
Pixham	6·45	7	9	—	—
Diglis	3·17	7	9	—	—

The flood current ran at the rate of 4·46 miles an hour at Newnham and Stonebeach. The bore advanced at the rate of from 6 to 13 miles an hour. The conditions of the river have been altered since these observations were taken, and the tide has been excluded from the upper part of the river.

The Yare. Yarmouth. Spring tides.

	Miles.	Average depth in feet. L.W.	Average depth in feet. H.W.	Rate of propagation of tidal wave in miles per hour. Foot.	Rate of propagation of tidal wave in miles per hour. Head.
Yarmouth Pier	0·00			—	—
Yarmouth Bridge	2·62			5·24	2·62
Burgh Flats	3·90			2·60	3·90
St. Olaves	4·93			4·93	4·93
Burgh St. Peter	5·56			5·56	11·12
Beccles	6·72			6 72	6·72
	23·73			4·72	5·27

The Ouse (Norfolk). W. H. Wheeler. Oct. 1883.

Lynn Dock	0·0	—	—	—	—
St. Germain's	3 5	11		7	28
Magdalen Bend	4·0	8		8	
Nar Bank	1·5	6		3	
Denver Sluice	5·0	8		10	
	14·0				

The Tees. Mr. John Fowler. 1885. Average of 13 tides.

	Miles.	Average depth in feet. L.W.	H.W.	Rate of propagation of tidal wave in miles per hour. Foot.	Head.
Bar	0·0	—	—	—	—
Cargo Fleet	7·0	11	30	13·05	39·15
Stockton	12·5	6	18	8·70	15·00

The Seine. M. Belleville. 1885.

Havre	0·00	—	—	—	—
La Risle...	12·00	10	32	8·00	36·36
Quillebœuf	8·69	15	35	26·30	26·33
Duclaire...	33·51	23	35	14·36	25·60
Rouen	22·96	15	25	18·46	11·48
Martot	14·90	13	21	18·00	29·80

The Humber. Report British Association and Tide Tables, 1864.

Spurn Point	0	—	—	—	—
Hull	23	40	60	16·30	32·40
Goole	23	10	22	7·38	17·00
Naburn	28	6	12	7·00	11·62
Hull to Gainsborough...	65	6	12	10·27	22·90

Tidal Predictions.—The calculations required to determine the daily time and height of the tides are exceedingly complicated, and involve the working out of an immense number of equations, from twenty to thirty constituents having to be dealt with. This duty is undertaken in this country by the Admiralty, and Tide Tables are annually issued by the department, giving the diurnal time and height of the tide at twenty-four representative ports round the coast of the British Isles, with constants by the aid of which the time and height can be found for almost every known port in the world.

For the purpose of saving human labour, a tide-predicting machine has been invented by Sir W. Thompson. The object of this machine is to predict the times and heights of the tides for a year for any port for which the materials are available from local observation. The records obtained by a tide-gauge are reduced to their constituents by harmonic analysis, by means of a machine also designed by Sir W. Thompson. For each tidal constituent the machine has a shaft with an overhanging crank, which carries a pulley pivoted on a parallel axis adjustable to a greater or less distance from the shaft's axis according to the range of the tidal constituents for different ports. A wire

or chain passes over or under all the pulleys, carrying a weight at one end, with a pencil attached which makes the curve on a band of paper. This machine can work off the whole of the tides of a port in about four hours. A description and illustration of these machines will be found in the *Min. Proc. Inst. C. E.*, vol. lxv.

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CHAPTER VI.

THE PHYSICAL CONDITIONS OF TIDAL RIVERS.

Rivers may be divided into three parts—

1. The fresh water or non-tidal portion.

2. The part within the coast-line confined within limited boundaries, through which the tide ebbs and flows.

3. The estuary, or the part where the coast-line opens out, leaving a wide mouth or bay.

Origin and Description of Rivers.—Rivers in their original condition were formed by the flow of the water off the land to the ocean, the development of their present shape and direction being due to the work of ages. In this part of the world they probably received their main characteristics after the breaking up of the Glacial Period, when the torrents due to the melting of vast masses of glaciers and icebergs, pouring off the land and flowing to the sea, cut deep channels and conveyed the material eroded in their course with them.

The vast areas of sand which are to be found in many estuaries are the result of this process. In the early condition of the river, the gradient and the velocity of the water would be much greater than they are now. The remains of river terraces in many valleys testify to the magnitude of the streams which then poured off the land. Gradually the forces of the erosive action of the water and the resistance of the soil balanced one another, and the struggle also between the tidal water and the ebb torrents resulted in an equilibrium being established between the contending forces, and the *régime* of the rivers as they now exist became established.

There are two sources from which the water flowing in a river is derived, distinguished respectively as tidal and fresh water.

The tidal water enters at the lower end, and is derived from the tidal wave of the ocean, which, as its crest passes the mouth of the river or its estuary, raises the level of the water during a period of a little over six hours, filling the tidal basin and causing a run of water up the river; during a similar period, as the trough of the tidal wave passes the estuary, the process is reversed. The supply of tidal water is thus constant, the same quantity passing out of the estuary on the ebb as entered during the flood.

The tidal motion continues as a wave so long as the depth of water in the low-water channel is sufficient for its generation, but is converted into a current as the depth shoals.

This supply of tidal water from the sea has enabled many rivers to be used for navigation which otherwise would not have had the necessary depth of water.

The water poured in at the upper end of a river also comes from the sea, but by a different process. This is due to the evaporation caused by the sun, the vapour formed being collected into clouds, condensed again, and in the form of rain falling on the land, and is then collected into the brooks and rivulets which feed the rivers.

The supply of fresh water, therefore, is limited, variable, and intermittent. This fresh water only travels in one direction. Obeying the law of gravity, it ever continues a constantly downward course, except during the time it is headed back by the tide, until it reaches the lowest point attainable—that is, the trough of the tidal wave.

In the middle zone of the river, between the purely tidal and the fresh water, the currents assume the oscillating motion due to tidal influence. The current alternately flows both ways, being driven back and raised up during the flood tide, and running down and its level depressed during the ebb. Under certain conditions, the action due to the tide may be simply a raising of the level without a reversal of the current.

Salt and Fresh Water.—The waters coming from these two sources vary in their character. That which is supplied from the sea is of greater specific gravity, and contains a larger amount of salts in solution, than that which comes from the land.

Pure fresh river-water, at a temperature of 60°, has a specific gravity of 1·00, and contains about 3·16 grains of salt in a cubic foot of water. Sea-water on an average has a specific gravity

of 1·026, and contains about from 6230 to 6853 grains, or nearly 1 lb., of salt in a cubic foot.

In the Dead Sea the quantity amounts to 34,738 grains, or nearly 5 lbs., in a cubic foot. In the Baltic, where there is a very large proportion of fresh and very little tidal water, the specific gravity is 1·005; in the Mediterranean the specific gravity is 1·029.

The greater density of sea-water prevents its rapid mixture with the fresh water in a river, and frequently two distinct columns of flowing water can be traced in the same stream. Fresh water rises on salt water, and flows on the top of it something in the same manner as oil. Thus, in the Gulf of Mexico, the water from the Mississippi may be traced in a column 7 feet deep on the surface, extending out from the shore, and slowly mixing with the salt water as the column is spread over a wider area and is agitated and broken by the wind. Beneath the fresh water there is a current of salt water setting into the river, while the fresh water on the surface is flowing out. At the mouth of the Rhone the river-water spreads out on the surface of the sea, the density of which is 1·027, in a layer which sometimes extends for 10 miles from the mouth. This layer of fresh water is so thin that the wash of a vessel suffices to bring the salt water to the surface.

The varying density of salt and fresh water affects the flotation of immersed substances. Stones and pebbles are more easily moved in sea-water, and vessels have a greater draft in the fresh water of a river than in the sea.

The proportion of tidal to fresh water varies considerably in different rivers.

In the Thames, the volume of tidal water in the river from Sheerness to Teddington was given by Mr. Mansergh at the Metropolitan Sewage Inquiry as 752 millions of cubic yards; the fresh-water flow as $2\frac{1}{4}$ millions, the tidal being about 331 times greater than the fresh. In the Humber the tidal water is 250 times as great. In the Mersey the volume of tidal water is 284 times greater than the fresh. In Cromarty Firth the flow of the spring tides is stated by Mr. Stevenson to be 1541 times greater than the fresh water in summer.

Agents of Maintenance.—There are two principal agents always at work in tidal rivers, one tending to shoal and deteriorate the channel, the other to maintain and deepen it.

The agencies which tend to shoal the channel are the transporting power of the fresh water, which brings detritus down from the upper reaches; the winds and waves, which erode the cliffs and banks; and the currents which disturb the sand-beds in the estuary. The material thus brought into the channel, if left at rest, rapidly subsides in the lower part and raises its bed.

The continual oscillation of the water due to the tides is the chief agent which keeps the detritus in motion and prevents its deposit. The current of the fresh water, always flowing in one direction, is the chief agent of transport which carries the material away out of the channel to the sea. Its capacity to transport the solid matter continues in a diminishing ratio until the termination of its course. As it approaches the tidal portion of the channel, the conditions of flow become so altered that the tendency to deposit is greater than the transporting force.

In a tidal river this solid matter is kept in movement by the oscillating action of the tides, until it is finally carried out to sea or deposited on the shores of the estuary, where it settles and forms the salt marshes to be found on the coast.

In non-tidal rivers, as the current slackens on approaching the sea, the material settles at its mouth and forms deltas.

The ever-continuous motion of the water in tidal rivers, and the constant reversal of the direction of flow, therefore, gives these rivers a great advantage over tideless rivers, in which the current of the stream is always in one direction.

Régime of Rivers.—Under natural conditions, the forces at work in a tidal river adjust themselves so as to establish an equilibrium between the eroding agency of the current and the tenacity of the soil of which the bed and banks are formed, and the slope becomes so regulated that the velocity is sufficient for the transport of the detritus.

When unconfined by banks, the direction also of the low-water channels through beds of sand and silt is the result of a balance of forces set up by gales, currents, floods, and other disturbing causes. A comparison of the charts of a sandy estuary extending over several years will show that, although at times the course of the channels may be altered by the prevalence of gales from one direction, of continued land-floods, or of long periods of dry weather, giving undue influence either to the tidal or fresh-water agency, yet there is one course, of a more or less stable

character, to which the low-water channel always reverts under normal conditions.

Junction of Rivers with the Sea.—The angle or direction in which a river joins the sea is affected by the shape of the adjoining coast, the set of the tide, the direction and force of on-shore gales, and the travel of littoral drift.

An examination of the charts of the coasts of this country will show that in the great majority of cases the line of direction of the main low-water stream where it enters the sea is nearly at right angles to the main set of the tidal stream along the coast, or inclining rather in the direction of the set of the tidal ebb and flow. In some instances, as in the Thames, the low-water channel curves in the direction to meet the set of the flood tide, and the same is, to a smaller extent, that of the Wash. The Humber, on the other hand, enters the North Sea at an angle of about forty-five degrees away from the direction of the flood tide. In the Ribble and the Mersey, the low-water channels passing through the sands generally trend in the direction of the tidal currents. In several cases, as in the Bristol Channel, the direction is directly in line with the set of the flood current. Many outfalls will be found to face the direction from which the heaviest on-shore gales come.

Source of Detritus in Rivers.—Although there may be exceptions, the material which a river has to deal with is supplied from the interior, and not from the sea. This may be proved by an examination of the material in suspension, or of the water coming in with the tide from the sea. Even where the tide flows over a vast mass of sands, such as those which lie along the coast outside the mouth of the river Mersey and the Ribble, or of the Humber and the Severn, it will be found that the tidal water flows into those estuaries bright and clear, and free from deposit, except in stormy weather, and that it only becomes turbid after it has mixed with the ebb. That a contrary view to this prevails is shown by the fact that Sir John Rennie, in his scheme for the reclamation of lands in the Wash, on the East Coast, calculated on the deposit of the material brought from the North Sea into the Wash in suspension. As a matter of fact, except in stormy weather, the water passes up Boston and Lynn Deeps bright and clear, free from any matter in suspension, and in stormy weather the sand which is stirred up is only rolled a short distance into the channel.

In the Severn, above the juncture of the Avon, the water in the river is very muddy, being largely charged with alluvial matter. The zone where the proportion of solid matter to water is greatest varies with the amount of freshets coming down. Below the Avon the channel gradually becomes less muddy, until off Swansea it is quite bright and clear.

The Ouse and the Trent are more fully charged with detritus than any river in this country. As in the Severn, the zone where the proportion of detritus is greatest varies with the quantity of fresh water coming down, but is always greater in these rivers than in the Humber, into which they flow. Samples of water taken by the author in these rivers and the Humber at the same time showed the following results. In the Trent below Gainsborough there were 261·87 grains of solid matter in a cubic foot of water; six miles above Trent Falls, where it joins the Humber, there were 3150 grains on the first of flood, the water itself being excessively turbid. In the Humber, at Spurn Point, during the flood tide, there were only 135 grains, consisting entirely of clean particles of sand, the water itself being bright and clear, showing that the material in the Trent could not have come from the sea.

It has frequently been stated that the material derived from the degradation of the clay cliffs along the coast to the north of the Humber is carried by the tide into that river, and is the cause of the large amount of alluvium to be found in suspension in the water. There is, however, no evidence of the water entering the Humber being discoloured by this alluvium, as would be the case were it carried into the river by the tide. The material of which these cliffs are composed is clay and boulders, the former of which soon becomes disintegrated and broken up into particles sufficiently minute to be moved about in suspension in the water so long as it is in motion. By the constant oscillation of the tides, these particles become diffused throughout a very large area of water, which gradually extends with each oscillation of the tide. Part of it also settles down to the bottom of the sea in calm weather at the slack of high and low water. Taking the volume of water in motion at the entrance to the Humber during the inflow of the tide and the quantity of material eroded from the cliffs, and supposing the whole of the material reaches as far as this, the calculation will be found to work out to only a very small fraction of a grain to

a cubic foot of the water. The travel of material in suspension in tidal water advances very slowly, being continually moved forwards and backwards, and with each oscillation becoming more widely diffused. It is, therefore, very improbable that any of this detritus is ever carried into the Humber, and certainly not into the Wash.

The vast areas of sand which are to be found in many estuaries are instanced as proofs that the sea is continually transporting material and depositing it in these receptacles. As already pointed out, however, an examination of the facts does not warrant any such conclusion. These sandy estuaries have maintained their condition with slight variation as long as any record exists, and must be due to some great alteration of climatic conditions. If the operation of transporting sand from the sea into the rivers were continuously going on, these estuaries would have been dry land many ages ago. The bed of the sea being at a lower level than that of an estuary, there must be a constant tendency, due to gravity, for the material to travel to the sea.

Ebb and Flood Currents.—The duration of the ebb in rivers and estuaries is longer than the flood, the difference depending on the low-water depth and the condition of the river. There is not, as a rule, any great discrepancy, especially in a river in good order, between the time actually occupied by the flowing and ebbing of the actual tidal water, the difference being taken up by the time required for the discharge of the fresh water coming down on the ebb, and of such of it as had been penned up and held back by the rise of the tide.

As soon as the flood tide begins to make up a river, the downward current is at first checked and finally arrested, and so long as the tide continues to flow, and until it has ebbed out again sufficiently low to allow of the escape of the fresh water, this is accumulating, the river being converted, as it were, into a reservoir to hold it during tide time. On the turn of the tide, there has then to be discharged, not only the ordinary supply of fresh water, but the quantity accumulated in the reservoir, and all the last part of the ebb consists of this, and not of tidal water.

Thus in the Mersey, as will be seen from the diagram given in the description of that river, between the bar and New Brighton during the two middle quarters of the flood

and ebb tide, the time of ebb and flood was about the same; and from high water to the last quarter the difference in favour of the ebb was less than half an hour, the difference during the time from low water to the first quarter being more than an hour and a half. Between Garston and Runcorn the flood only lasted 3 hrs. 20 min., taking 6 hrs. 10 min. for the ebb to fall to low-water level.

The greatest velocity of tidal water is at about half-flood or half-ebb. At the first quarter of flood it has to reverse the action of the ebb, and has shallower water in which to propagate itself. In the first quarter of ebb the direction of the stream has to be reversed, and at first the inclination of the surface is less than that which later on occurs. In the middle period the water moves with the greatest velocity, and then the rise and fall is nearly twice as much as during the first and last quarters. That the motion of the water is greatest at this period is shown by the action of floats, the greatest progress being made with these at half-flood and half-ebb, and the least near low water and high water.

The ebb has an advantage over the flood in not having to expend the same amount of energy in reversing the direction of the current. The flood-current has to create its own head. Having arrived at high water, there is a period of slack. The natural action of gravity of water flowing from the higher level of the river assists in carrying the ebb water downwards, and in transporting the material in suspension.

The flood tide has a greater erosive action than the ebb. Where the last of the ebb consists of fresh water, the flood, owing to the greater density of the salt water, drives its way in a wedge-shaped form under the fresh water, exerting an eroding action which loosens the particles of alluvium which had settled on the bottom, and, by placing them again in suspension, facilitates their removal by the ebb. The flood is therefore a valuable agent in keeping the channels open.

As the tide rises and the water begins to cover the sandbanks in an estuary, the flood has to overcome the resistance due to gravity, and has to lift the material it has in suspension up the inclined plane presented by these banks, and roll the particles along the sand, and has also to overcome the friction due to the rubbing of the water along the sand. Although, therefore, the flood may come in with a greater momentum and velocity than

the ebb flows out, its energy is dissipated in overcoming these resistances.

Evidence is further afforded of the preponderating effect of the ebb over that of the flood by the fact that, in addition to transporting back any material brought up by the flood, it has also to carry away out of the channel of the river or estuary, the alluvial matter brought down by the river in floods. Apart from disturbance caused by fresh-water floods, the effect of the ebb and flood currents is equal. The movable material disturbed by the water oscillates backwards and forwards with the tides, travelling greater or less distances as the springs or neaps prevail; but the detritus that comes with the fresh water is new matter, and, unless moved clear of the channel, would in time fill it up. The duty of its removal is performed by the same agent that brings it—that is, the fresh water.

If material were brought in from the sea in a greater quantity than the ebb could carry back, the tidal estuaries and rivers must have ceased to exist many ages ago. If, on the other hand, the ebb were continually carrying out a greater quantity of material than the flood brings up, the channels would go on continually deepening. There are numerous examples of bays and narrow inlets running a long distance from the sea inland, where no disturbance occurs from the admission of land freshets, and where the water is purely tidal. The regular ebb and flow of the tides maintain these channels in a stable condition, and there is sufficient evidence to show that they have remained in the condition in which we now find them since the last great change in the physical condition of the country took place.

As an example of this may be quoted Southampton Water, which is a channel five and a half miles long and about half a mile wide, between banks of soft mud which are covered at high water, and which has a depth of from 9 to 5 fathoms at low water. Its connection with the sea is by the narrow strait of the Solent, between the coast and the Isle of Wight, through which the tidal water has to travel fifteen miles, and by the channel on the east side of the island, which meets the other at the mouth of Southampton Water. The river which empties into the head is too insignificant to keep such a large channel scoured, and if deposit were brought in by the tides from the sea, this channel would rapidly have filled up.

Tidal water alone, although very much larger in volume

than the fresh water, has not the same effect as upland water in carrying material out of the channel. The quantity of water coming in with the tide being the same as that which goes out, the material moved on the bottom will not greatly differ in quantity. What is rolled up by the flood will be rolled back by the ebb, the latter having rather the advantage; but with matter in suspension the case is different. This becomes diffused throughout the increased volume of water due to the tide, and the quantity left in the water in the river is so much less by that which has passed out with the tidal water; the quantity will depend on the distance any particular section is from the sea. The tidal water from the section nearest the sea all passes out of the river; when a certain distance is reached, the water in the river is only driven back, and a partial diffusion only takes place; in the upper part of the river no sea-water reaches, and here the quantity of matter in suspension is not affected by the tidal influence.*

The rate of actual travel forward of material brought into a river by land floods, or eroded by the action of the water, depends on the amount of fresh water, and its effect in strengthening and prolonging the ebb. As an illustration of this, the case of the Trent and the Ouse may be taken. These rivers, as already mentioned, contain a very large quantity of matter in suspension, brought down in freshets from the large area of land which they drain, and also from the solid matter contained in the sewage discharged into them, which cannot amount to less than 15,000 tons a year. The quantity of solid matter in suspension at certain seasons is so great that, if the water is allowed to flow on and off land adjacent to the rivers and remain there, it will cause a deposit at the rate of from 2 to 3 feet in a season. This process can only be carried on in summer. When freshets are coming down the river, the ebb current is so strengthened as to keep the material continually moving downwards, and in long-continued wet weather it reaches the sea; but under ordinary conditions a large proportion does not get beyond the lower reaches of the river. As the freshets fall off, this is again brought up by the flood and carried back by the ebb, thus continually oscillating backwards and forwards in the rivers.

Professor Unwin, in a pamphlet published in 1883 on the effect of tidal water with reference to sewage discharge in a river,

* See note, p. 142.

states that, as the results of calculations which he had made, he had arrived at the conclusion that the direct effect of upland water pouring into a tidal river is to displace down-stream all the water below it by a distance which at each point is equal to the length of the river-bed which the upland water would occupy. In the upper part of the river the displacement due to the upland water might be considerable, and here the upland water must have a large influence in maintaining the *régime* of the river. In the lower reaches the displacement due to the upland water is small compared to the tidal oscillation, and the effect of the upland water in carrying material seawards is extremely slow. Thus he calculated that in the Thames it would take, during an ordinary winter flood, 65 days to discharge at Sheerness material entering the river at Woolwich, a distance of 31 miles. In summer he estimated the distance at one-third of this, and during excessive floods the travel might be increased to eight times the above. He considers that the main effect of tidal water is to drive back the water which, at the end of the ebb, occupies the river channel. In each length of a river the water is driven back a certain distance, and, apart from the mixing action which goes on, no water coming from below will reach a higher point in the river. Thus, for example, in the Thames, water at Sheerness is driven back 10½ miles, and no water from below Sheerness reaches a higher point in the river; the water at the end of the ebb at Erith is driven back 8 miles to Woolwich, and so on; and so water at the end of one ebb at Woolwich is driven back 10 miles, less the amount due to the displacement caused during tidal flow by the upland water. At the end of the next ebb it travels back 10 miles plus the displacement due to the upland water, or say half a mile lower down than at the previous ebb; the conclusion being that tidal action alone effects directly no change in the material water in the river, but merely a reciprocating oscillation over a certain length. If, therefore, there were no mixing action between water driven up by the tide and that initially in each compartment, the river would, down to the sea, become ultimately entirely fresh water. If, on the other hand, the supply of upland water were stopped, the whole water in the river would become of the density of salt water.

Observations as to the extent of the oscillation of the tidal water in the Thames have been carried out at different times

with reference to the inquiries made as to the discharge of the London sewage into the river, the details of which will be found in the report and evidence of the Royal Commission on Metropolitan Sewage in 1883.

Proceeding on the same lines as Professor Unwin, Mr. Baldwin Latham endeavoured to show that the actual travel of the fresh water, and its effect in carrying solid material to the sea, could be shown by the proportion of chlorine in any given section of the river. He treated the actual quantity of fresh water coming over Teddington Weir as a column occupying a certain space and working its way out to sea through the larger volume of salt water with a certain velocity. The normal amount of chlorine found in the estuary at the mouth of the river being determined, the quantity of chlorine found in any given section would show what proportion of this area was occupied by salt water and what by fresh water. The proportion of the area occupied by the fresh water divided by the volume would give the velocity or rate of travel of the fresh water. The rate at which the fresh-water column must travel to carry out a given volume being thus determined, it was calculated that with an ordinary discharge of about 1390 cubic feet a second coming over Teddington Weir, it would take 12 days to reach Barking, $30\frac{1}{4}$ miles, and 30 days from there to Southend, $33\frac{1}{4}$ miles. Whereas when the quantity of fresh water was increased sixfold by a flood to about 8000 cubic feet a second, the rate of travel was 3 days to Barking, and 11 days from there to Southend, this showing the much greater effect which the fresh water has in transporting deposit in the upper reaches, where the fresh water bears a larger proportion to the tidal than in the lower reaches.

Floats have also been placed in the river and allowed to oscillate up and down for several days. The first observations were made by Mr. Phillips in 1851, with floats 6 feet long, and 15 inches square at the bottom and 6 inches at the top. These floats were put in the river at Barking at a time when there was very little fresh water flowing down. The floats, on the average, went up with the flood 12 miles, and back down with the ebb $12\frac{1}{6}$ miles, showing a downward advance of only one-third of a mile per day. Other observations made from June to August showed, as the result of 74 runs, an average rate of 11·98 miles up and 12·64 miles down, or a daily advance of $1\frac{1}{3}$ mile down.

It was found that as the tides took off from the springs the ebbs became more powerful, and at the neaps the floats made a greater advance downwards than at springs. In 1882 further observations were made by Mr. P. Birch, under Mr. Latham's directions. The floats were octagonal, 12 feet 6 inches long, 11½ inches diameter, and immersed 12 feet. The floats were put in at Barking in September, respectively at high water, at half-ebb, and at low water, and each set allowed to float up and down the river during two lunations. During this period they descended on an average two miles. The float put in on the top of the spring tides descended during the springs 15 miles, and ascended within 2·77 miles of the starting-point; during neap tides it descended 17·56 miles, and ascended within 7·65 miles of the starting-point. The average distance travelled each tide by the floats upon all ebb tides was 12·64 miles down, and on floods 12·60 miles up. The fresh water passing over Teddington Weir at the time was rather above the summer average.

The observations were not extended over a sufficiently lengthened period to show what the increased rate of travel would be when a freshet was coming down the river, but some limited observations taken when the quantity of water coming over Teddington Weir had increased above the normal summer flow, showed that the rate of downward progress of the floats rapidly increased with the increase of fresh water.

Float experiments have also been made in the Clyde at different periods, the results being recorded in a report on "The Tidal Velocities in the River Clyde," by Mr. James Deas, issued in 1881. The floats used in the earlier experiments were 3 feet long by 3 inches square, weighted at the bottom so as to keep them upright. Subsequently the length was increased to 11 feet, and the diameter to 4 inches. Wooden floats made in the form of a cross were also used. These were 2 feet 6 inches wide, each arm of the cross being 6 inches wide and 1 foot 4½ inches deep. A lead weight was attached to the centre at the bottom, the whole of the cross being immersed, and only a point of wood projecting. Oranges were also used as surface floats. Some of the experiments were made in 1879, before the weir across the river above Glasgow was removed, and others in 1881, after its removal. They were conducted in the month of June, when only the ordinary amount of summer fresh water was running down the river. The floats were started from Glasgow

bridge, and were watched night and day. In 1879, in ten tides the floats reached Gourcock Bay, 24 miles down, being at the rate of 2·42 miles per tide. In 1881, after the same number of tides, the floats reached Fort Matilda, 23·5 miles, or at the rate of 2·35 miles per tide. These are average results. Of six trials the slowest advance was 1·68 mile per tide, and the quickest 3·36 miles.

The result of experiments conducted by the author in the river Witham, showed that a solid wooden float, 6 feet long, 12 inches square, and floating six inches out of the water, started from the entrance to Boston Dock half an hour after high water in 6 hrs. 21 min. travelled down the river to Clayhole, 6·65 miles, the last two miles being in the open estuary outside the river. It remained stationary an hour, and returned to its starting-place in $3\frac{1}{2}$ hours, reaching there about one hour before high water. The rate of travel on the ebb was 1·12 mile per hour, and on the flood 1·99 mile. The motion of the float in this experiment was due entirely to tidal influence, there being a total absence of fresh water in the river. The tides were springs, the rise above low water being about 18 feet at the upper end, and 22 feet in Clayhole. Subsequent experiments, although varying a little as to the time occupied, took the float to the same point below on the ebb and brought it back to the starting-point on the flood.

Tests made with solid floats cannot be relied on to give a correct result as to the amount of matter carried by the water in suspension. During the time the float is travelling a certain distance down the river, an immense volume of water has been displaced and gone out to sea, carrying with it a large quantity of suspended matter, which becomes deposited in the

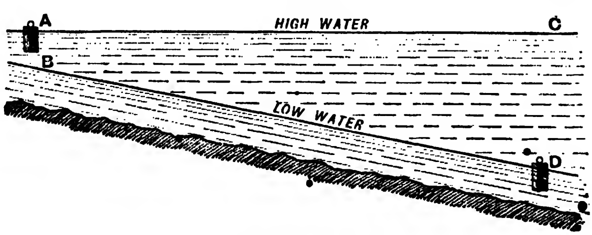

FIG. 11.—Diagram showing motion of float.

bed of the ocean, or is too dispersed ever to return. While the solid body of the float is simply carried along by the current, the matter in suspension is continually changing its position by

the action of the water, the particles, being thrown up from the bottom and rising to the top, becoming diffused throughout the whole mass, and moving away with the tidal water. This is shown more clearly by the diagram, Fig. 11. The float is shown as having moved from A to D on the ebb. The shaded space between the letters A B C D, represents the tidal water which has flowed out to sea.

Effect of obstructing the Free Flow of the Tide.—Any cause that obstructs the flow of the tidal water and the free propagation of the tidal wave, is detrimental to the maintenance of a river in its most effective condition, and leads to the shoaling of the channel.

The placing of weirs across tidal rivers, contractions of the channel and irregularities in its form, restricted entrances, and similar causes, are destructive to the maintenance of a deep-water channel.

In the river Ouse, in Yorkshire, the tides have been excluded from the upper part of the river by a weir and lock placed across the river at Naburn, about 28 miles above Goole. In summer deposits take place below the weir to the extent of 5 to 10 feet; and in a dry season it accumulates in the river between Naburn and Selby, a distance of 10 miles, to such an extent as to reduce the navigable depth nearly 4 feet, seriously impeding the navigation to York. This deposit is removed more or less entirely by the winter freshets.

In the Witham, the landowners interested in the drainage of the fenland obtained powers in the middle of the last century to straighten the upper part of the river, and to exclude the tidal water by a sluice and lock placed across the river above the town of Boston, about 8 miles from the sea (see illustration in the description of the Witham). The portion of the river between Boston and Lincoln, in addition to forming the main drain of that portion of the fenland, was used as a canal navigation. At the time when this sluice was erected, and until a few years ago, the outfall of the river passed through a mass of shifting sands before it reached the deep water of the estuary, and was continually altering its course. The flood tide, working through these sands, carried in suspension and drove up the river along the bottom large quantities of material. The momentum of the flood tide being checked on arriving at the sluice, a reaction is caused, and a back current is generated, which, meeting the

succeeding tidal wave, converts a flowing stream into slack water. The deposit which was formerly brought up by the tide remained behind when the water receded, and gradually accumulated, raising the bed of the river, not only immediately adjacent to the sluice, but, from the absence of any tidal back scour, for a considerable distance down the river. In dry seasons, when there has been a lack of fresh water, the deposit has accumulated against the sluice to a depth of 10 and 11 feet, tailing off to 3 and 4 feet at 4 or 5 miles down the river. When this occurred, vessels were unable to reach the quay at the town, and had to lie in the estuary and discharge their cargoes into lighters. That this accumulation was entirely due to the stoppage of the flow of the tidal water may be proved from the fact that in the Welland, a much smaller river, which discharges into the same part of the estuary, and which has a free tidal run of 20 miles, no such accumulation took place. A new channel having been made for the river Witham, and its outfall carried below the shifting sands, the current of fresh water is able to transport the small amount of sediment which is now in motion, and what little accumulation takes place is confined within a mile below the sluice.

In the rivers Vire and Aure, which flow through Vays Bay to the English Channel, on the north coast of France, doors were placed across the outfall at Vay bridge to prevent the tidal waters flooding the land. By this means about 80 million cubic feet of tidal water was excluded each tide from flowing up and down the outfall. Owing to this the channel silted up, and the navigation was almost stopped. Subsequently the doors were removed, with the result that the navigation became restored to its original condition.

The free propagation of the tidal wave may also be obstructed by irregularities in the form of the channel, by the existence of alternate wide spaces and contractions, and by shoals in the bottom. Wide spaces allow of lateral diversions from the flowing stream, which eddy round and disturb the forward motion of the particles. In like manner abrupt bends and restrictions in the width of the channel, by opposing a resistance to the direction of motion, check the momentum, and require a greater head to force the tidal water round them. As an illustration of this, the case of the tidal river Ouse, in Norfolk, may be taken. Between Lynn and Downham there is a horseshoe bend of about

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67 chains in length, the distance in a straight line being 37 chains. From about one-quarter to three-quarters flood, the inclination in the surface of the tidal water through the bend is at the rate of 14 inches per mile, as compared with from 2 to 4 inches per mile in the straighter reaches of the river.

The propagation of the tidal wave may be further affected by a restricted tidal entrance preventing sufficient water from getting into the river to fill the upper reaches. When the high water at the end of the tidal flow does not reach the same level as the tide in the open estuary, it is evident that the tidal wave is not being freely propagated. In some ports the depression of the level becomes a serious drawback from their navigable capacity. Mr. Stevenson states that on an average the tides in Montrose Bay, which has an area of 1200 acres, are 9 inches below the level of the water outside, the entrance not being sufficiently capacious to allow the tide to fill the basin during flood.

The river Nene affords an instructive example of the effect of contractions in the channel, and of abrupt bends. It drains 1055 square miles, and has a tidal run of 31 miles. This river discharges into the Wash, on the east coast of England, and has to find its way through about 4 miles of sands before it reaches deep water. Above these sands the river has been trained and straightened for 6 miles, and above this to the town of Wisbech, $10\frac{1}{2}$ miles from the outfall, it passes through a straight artificial channel. At Wisbech the river is restricted in width and area, and there are two sharp bends. Thence to Guyhirne, 7 miles, it passes along the natural course, which has from time to time been straightened and improved; and from Guyhirne to Peterborough it has a nearly straight course. In this reach there are some gravel shoals, which considerably diminish the depth of the channel. A spring tide flows $3\frac{1}{2}$ hours at Sutton Bridge, 4 miles from the outfall, and ebbs $9\frac{1}{4}$ hours. The ebbs fall at the rate of 17 feet 3 inches for the first $4\frac{1}{2}$ hours, and 6 feet 3 inches for the $4\frac{3}{4}$ hours of the rest of the tide. Sir John Coode, in a report made on this river in 1874, and from which the particulars and the diagram here given are taken, found that an average spring tide, which ranged 20 feet 1 inch at the end of the trained portion of the river, ranged 21 feet 4 inches at Sutton Bridge, $4\frac{1}{4}$ miles higher up. At Wisbech, $10\frac{1}{2}$ miles, the high-water level was practically level; whereas at Northey Gravel, where the range was 14 inches, the high-water level was 6 feet 4 inches

lower than at the outfall. The fall in the surface of the water at high water *towards* Peterborough was a little over 2 inches per mile from the lower end of the trained channel to Wisbech, and above this it was at the rate of 15½ inches per mile, falling towards Peterborough. The two bends and the contracted area of the channel through Wisbech and through the town bridge caused a sudden rise from 5·3 inches per mile to 17·7 inches. When it was high water at the outfall, the flood tide had just begun to run at Cross Guns, 25½ miles up the river, and above this the ebb was still running down. The accompanying diagram, Fig. 12, adapted from Sir John Coode's report, will show the condition of this tide in the river. The shaded parts represent corresponding half-hour intervals of the flood and ebb. It will be seen that, while the tide had run down at the outfall to the extent of 6 feet 11 inches for the two hours between 6·30 and 8·30, it was running up at Cross Guns in the same period to the extent of 6 feet. Thus there were two currents running in opposite directions, the summit level being about halfway of the whole tidal run. These abnormal conditions clearly indicate that the obstacles in the channel at Wisbech materially check the propagation of the tidal wave. The sectional area through Wisbech is not sufficient to allow the channel above to be filled at the same rate as the tide rises below the town, and hence the sudden increase in the inclination in the surface of the flowing tide. If the channel were adequate to its work, the tide would reach Peterborough sooner and rise higher than it does at the present time. The owners of the land lying adjacent to the upper part of the river have, however, successfully resisted attempts to improve the river through Wisbech by cutting off the bends, and also in the upper reach by removing the shoals, because they were advised that such improvements would be detrimental to the quality of the fresh water, which is drawn from the river for the use of the inhabitants and cattle, by allowing the boundary-line between the fresh and salt water to be extended further up the river.

In the Tyne, before the river was improved, it was not unusual to find the level of high water at Newcastle from 7 to 10 inches below that at Tynemouth.

In rivers favourable to the flow of the tide, and having trumpet-shaped mouths and funnel-shaped channels, that is, having their banks gradually converging, the opposite effect is

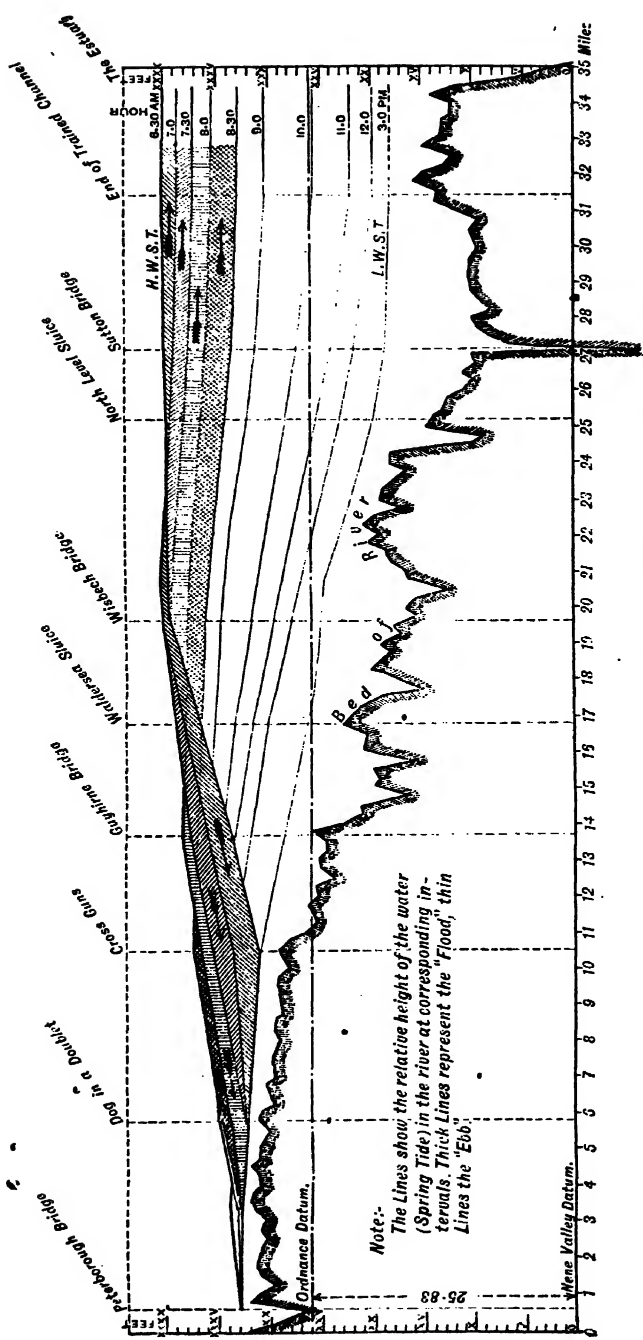


FIG. 12.—Tidal diagram of River Nene.

found to that experienced in the Nene, the momentum carrying the tidal water to a greater height than it attains in the estuary, and the reaction on the ebb lowering the low water lower. Examples of this will be found in the chapter on "Tides."

Width of Tidal Channels.—The width and sectional area of the upper part of tidal rivers bear a certain relation to their drainage areas, and to the volume of fresh water they have to discharge, although that quantity may be only a small proportion of the tidal volume which flows up them. The width and depth of the lower or purely tidal part does not appear to depend on causes now operating. The supply of tidal water being sufficient to fill the receptacle, however large, the form being once fixed. the channels are maintained by the tidal flux and reflux. Although no definite proportion exists between the width of the channel and the tidal conditions in estuaries in their natural state, yet it may be taken that approximately a convergence of the coast-line at the rate of from 1500 to 2000 feet per mile is conducive to the maintenance of deep-water channels. In the upper or trained portion of the channel of rivers where the rise of the tide is moderate, a convergence of from 50 to 60 feet per mile for the low-water width, but opening out more rapidly when approaching the outfall, gives satisfactory results. The increase of width of natural channels is not, however, gradual, but the proportion of increase augments rapidly downwards. In the following examples this has not been taken into account, the average rate of increase only being given.

The Thames, with a drainage area of 5162 square miles, a tidal run of 62 miles, range of spring tides at the mouth of 16 feet, widens out very rapidly at the lower end. Between Maplin Sands and Yantlet Spit, the rate of decrease in the width at the high-water level is 1694 feet per mile for seven miles; from Yantlet Spit to Woolwich, a distance of 30 miles, the channel decreases at the rate of 520 feet per mile at the high-water level, and 198 feet in the low-water channel; from Woolwich to London Bridge, 10 miles, the decrease at the high-water level is 71 feet, and at low water 62 feet, per mile. Above London Bridge there is no regular decrease, the width at low water varying from about 700 feet at London Bridge, to 720 feet at the Embankment, 745 at Battersea, 1000 at Chelsea, and 820 at Fulham.

The Humber has a drainage area of 10,500 square miles,

a tidal run, including the Ouse, of 65 miles, in addition to which the tide has a long run up the Trent. The range at the mouth at spring tides is 19 feet. From a short distance above Spurn Point to Sunk Island, a distance of 10 miles, the estuary decreases at the rate of 2550 feet per mile at high water, and 1350 in the low-water channel. From Sunk Island to Hull, 13 miles, at the rate of 430 feet and 146 feet respectively. From Hull to the junction of the Ouse, the decrease is at the rate of 516 feet per mile; and from Hull to Goole the low-water channel decreases at the rate of 310 feet per mile; and from Goole to Naburn, where the tidal run is stopped, 20 feet per mile. The low-water width at Hull is 8200 feet, and at Goole 700 feet.

The Severn has a drainage area of 8000 square miles. The length of the open estuary from Hartland Point to Portishead, where the river channel may be said to begin, is 85 miles; from here to Gloucester, where the tidal run is now stopped, is 30 miles. Formerly the tide ran nearly to Diglis Weir, about 37 miles further. The tidal range in the estuary is 27 feet, but rising to about 42 feet at Portishead. The estuarial portion, which is 42 miles wide at the lower end, decreases at high-water level to 3 miles at the upper end, or at the rate of 2429 feet per mile. From a little above Portishead to Gloucester, the decrease in the low-water channel is at the rate of 110 feet in the mile.

The Ouse (Bedfordshire) has a drainage area of 2894 square miles, a tidal run of 42 miles, and a range of tide of 23 feet. This river, in the lower part for the last five miles, has been considerably altered, the channel having been straightened, deepened, and trained for a short distance into the estuary. The middle portion has not been altered; the upper 20 miles, through which the tide flows, is an artificial channel. The lower five miles decrease at the rate of 25 feet per mile, the middle or natural portion at the rate of 5 feet, and the upper at the rate of 1 foot. Notwithstanding the small increase in width of this channel, the tide flows for a long distance, the level of high water at Denver Sluice and in the estuary, 16 miles away, being level, and 1 foot 4 inches lower at the end of the tidal run. The tide is propagated between these places at the rate of 6½ miles an hour on the flood, and 27 miles at high water.

The Scheldt has a drainage area of 8000 square miles, a tidal

run of 105 miles, and a range of tides at the mouth of the estuary of 15 feet. From the mouth of the estuary below Flushing to a little below Lillo, a distance of about 35 miles, the width at high water is about three miles, and varies very little. Above Lillo the channel suddenly contracts to about one-third of the lower width, and from here to Antwerp, a distance of 12 miles, the decrease in width of the channel is at the rate of 106 feet per mile at high-water level, and 89 feet at low water.

The above are examples of rivers more or less in a natural condition; the following, of rivers which have been improved and their width made uniform by training works.

The Clyde has a drainage area of 945 square miles, a tidal run of 30 miles, and a range of tide at the mouth of the trained channel of 11 feet, and depth at low water of 15 feet. The tidal water, coming up the Firth of Clyde, flows into an estuary about three miles wide, and disperses into Loch Long and Loch Gare on one side, and up the Clyde on the other. At Port Glasgow the channel is half a mile wide at low water, and two miles at high water; decreasing at Dumbarton Castle, four miles up the river, to 1 mile and 1000 feet respectively, or at the rate of 1320 feet for the high-water level, and 410 for the low water. From Dumbarton, for the next $3\frac{1}{2}$ miles up the river, the decrease is at the rate of 110 feet per mile; and for the next $8\frac{1}{2}$ miles to the lower end of the harbour at Glasgow, at the rate of 27 feet per mile, the width here being 370 feet.

The Tyne has a drainage area of 1142 square miles, a tidal run of 19 miles, a range of tide of 14 feet, and depth of water at low water of 20 feet. Taking the channel as 1000 feet wide at Shields and 400 feet a little above Newcastle, or say for a length of ten miles, the average decrease is at the rate of 60 feet in a mile.

The Tees has a drainage area of 750 square miles, a tidal run of 26 miles, depth at low water of from 8 to 10 feet, and range of tide $15\frac{1}{2}$ feet. Taking the width between the lower end of the two training walls, about a mile above the breakwater, at 1100 feet, and as 552 feet $4\frac{1}{2}$ miles up near to Middlesborough, the decrease is at the rate of 122 feet per mile. The channel opens out for the last $1\frac{1}{10}$ mile at the lower end at the rate of 360 feet per mile. Above Middlesborough up to Stockton the decrease is at the rate of about 42 feet per mile.

The Dee has a drainage area of 862 square miles; the length of the tidal run from the bar to Chester is 25 miles, but

spring tides run over a weir, and for a distance further up the river of about 7 miles. The range of tides at the bar is 26½ feet. The open estuary from the Point of Ayr contracts very regularly for about 10 miles at the rate of 1584 feet per mile at the high-water level. The low-water channel through the sands is not well defined, and splits into two main channels at the lower end. For the first 4 miles the rate of decrease is 1150 feet per mile, and for the 6 miles above this the decrease is at the rate of 141 feet per mile. In the trained portion of the channel, the low-water channel decreases for the first three miles to Queen's Ferry at the rate of 55 feet per mile, and thence to Chester, 6 miles, at the rate of 11 feet per mile. From the results which have been obtained, the rate of decrease is not sufficient for the trained portion of this channel.

The Ribble has a drainage area of 800 square miles, a tidal run of about 20 miles from the bar, and also about 10 miles up the Douglas. The range of tide is 27½ feet at the bar. This river discharges through a very wide sandy estuary, the width at the upper end of which has been considerably reduced by enclosures of marshes, but the embankments have improved the form of the estuary by making the coast-line more gradually converge towards the upper end. The width between St. Anne's and Southport is about 8 miles; at 10 miles above this the width now is half a mile, making the rate of decrease about 4000 feet in a mile, whereas before the enclosures the decrease was only 3300 feet. The low-water channels are divided into two, but taking the width of the two together at the lower end as 2000 feet, and the width at the end of the double training walls as 370 feet, the decrease is at the rate of 200 feet per mile. The channel has been trained for 5 miles, down to the junction with the Douglas, with double training walls, the width decreasing at the rate of 20 feet per mile. At present a single wall only has been carried down for about 6 miles below the river Astland, but it is intended that the channel shall be fined so as to decrease at the rate of 98 feet in a mile over this length.

The Mass. The training works of this river between the North Sea and Rotterdam were first laid out at the lower end so as to decrease at the rate of 105 feet per mile. This was found to be too great a width to obtain the full benefit of the scouring action of the water, and the channel has since been regulated so as to decrease regularly from the pier ends in the North Sea up

to Rotterdam at the rate of 65·5 feet per mile, the width at the upper part being 984 feet, and at the lower end 2296 feet. The tidal range is only 5 feet 6 inches.

The Seine has a drainage area of 30,370 square miles; a tidal run of 93 miles from the lower end of the estuary, and 79 from the end of the training walls. The range of tide is 23 feet at Havre. The depth at low water in the trained channel varies from 10 to 25 feet. The width of the estuary opposite Havre is $5\frac{1}{4}$ miles. The coast-line decreases to 3 miles at 11 miles up, but the width of the estuary at the present time may be taken at $1\frac{1}{4}$ miles, giving a rate of decrease of 1000 feet in the mile. The low-water channel through the sands is split up, but, taking the line of deepest water, the width may be taken at about a third of a mile to half a mile, there being very little variation in this width throughout the whole length. The trained portion was made originally 2296 feet wide at Berville, decreasing to 1640 at Tancarville, 4 miles, or at the rate of 164 feet per mile. Over the next $21\frac{1}{2}$ miles to St. Mailleraye, where the channel is 820 feet wide, the decrease is at the rate of 38 feet per mile. Above this to Rouen, $37\frac{1}{2}$ miles, where the width is 500 feet, the channel is very much in its natural condition, decreasing at the rate of $8\frac{1}{2}$ feet per mile. The width of the trained channel at the lower end has not been found sufficient for the easy admission of the tidal water, the first of the flood rushing up at great velocity, causing a bore.

The Gironde has a drainage area of 35,000 square miles. The range of tide is $16\frac{3}{4}$ feet at the mouth, and 18 feet at Bordeaux. The depth in the navigable channel at low water at Bordeaux is about 7 feet; this gradually increases to 3 and 4 fathoms. At the entrance at Royan the depth is from 10 to 16 fathoms; it then shoals again to $4\frac{1}{2}$ and 5 fathoms, and increases at its junction with the Bay of Biscay, where the depth is 9 fathoms. The outfall of this river, like that of the Loire, consists of a narrow estuary nearly 50 miles in length, which contracts very much at its termination on the southern side. The coast on the north side projects considerably beyond that on the south side. The distance apart between the two extreme points is 16 miles. At 9 miles up, at Royan, the width of the estuary is 3 miles; it then suddenly widens out $5\frac{1}{2}$ miles, and continues at about this width for 16 miles to Port Maubert. At the junction of the Dordogne, 45 miles from Royan, the width at

high water is about 2½ miles. The rate of convergence from Port Maubert is 592 feet in the mile; from there to Bordeaux, 15 miles, the contraction is at the rate of 120 feet in the mile, the channel being about 800 feet wide. The level of high water at Bordeaux is about 2 feet higher than at the mouth of the estuary.

The Loire is 607 miles in length, being the largest river in France. It has a drainage area of 44,000 square miles; a tidal run of 40 miles from the outer end of the estuary in the Bay of Biscay; a range at spring tides of 15½ feet at the lower end, and 5½ feet at Nantes, 30 miles up. The estuary, which is 6⅓ miles across, contracts to about 1¼ mile at St. Nazaire, 6 miles above; it then immediately widens out again to over 2 miles, maintains the same width for about 10 or 11 miles, and then gradually contracts. The average rate of decrease above St. Nazaire is about 600 feet in a mile at high water, and 254 feet at low water, the channel being about 700 feet wide at Nantes. The channel of the river below Nantes is much encumbered with sandbanks, and very irregular. The depth of water in the channel is not more than 3 feet at low water over the shallow places, and 16 feet at high water of spring tides; a bar stretches across the mouth of the estuary, on which there is only 9 feet at low water. Outside the bar the water deepens rapidly to 3 fathoms. At the narrow neck of St. Nazaire there is a deep pool, having from 40 to 60 feet at low water. The width of the upper part of the channel has been regulated by training banks between Nantes and St. Pellerin, and the depth has much increased. From Pellerin to Pambœuff the course of the river is much obstructed by shoals, which are uncovered at low tide. A large amount of dredging has been carried on, and the shoalest part of the river, over which there is only about 15 feet at high water, has been reduced to about four miles. The bad condition of this river for navigable purposes, and its inability to maintain a deeper channel, is due to the want of convergence in the channel, and the restricted tidal entrance at St. Nazaire.

The Weser is 355 miles in length, has a drainage of 18,000 square miles, and a tidal run to a little above Bremen, 45 miles from the mouth. The rise of spring tides is 10¾ feet at the mouth, and 4¼ feet at Bremen. The tidal portion of the river in its natural condition was very irregular in width, being encumbered by large shoals, which in several places divided the deep-water channel into two parts. It has recently been trained

and deepened between Bremen and Bremerhaven 40¼ miles. The high-water channel increases from Bremen at the rate of 110 feet in the mile, and the low-water channel at the rate of 78·66 feet per mile. The coast-line below Bremerhaven spreads out in a trumpet form for 10 miles, increasing at the rate of 3432 feet in the mile, the low-water channel increasing at the rate of 416 feet in the mile.

Straight and Curved Channels.—A river in its natural condition never runs in a straight line, but in a series of bends of varying curvature, depending on the nature of the soil and obstruction to the course of the water.

Abrupt bends are detrimental to the maintenance of rivers, causing disturbances to the flow of the water and difficulties to the navigation. Curves of large radius have an advantage in tending to maintain a more regular deep-water channel than exists in straight reaches.

That curved channels do not afford any serious impediment to navigation may be inferred from the fact that the Thames, along which as great a number of vessels pass as on any river in the world, and over the lower part of which the largest passenger-steamers afloat are daily navigated, has no less than fourteen bends between its lower reach and London Bridge, or an average of one bend in every two miles. The sharpest curve is at Blackwall, and has a radius of 1914 feet, with a width of channel of 1000 feet; and at Greenhithe there is a curve of 3960 feet, with a width of channel of 2000 feet.

In the Tyne, in Shields harbour, the river bends with a radius of 2000 feet, with a width of 900 feet; a second curve near the Northumberland Dock has about the same radius; and near Bill Point, about half-way to Newcastle, are two curves near together, each having a radius of 1300 feet, and a width of channel of 650 feet.

On the lower part of the Clyde there were, until recently, two curves, one at Garvel of 3400 feet radius, and one at Cartsdyke Bay of 1850 feet. These have been eased to 4300 feet and 3700 feet respectively, the width of the channel being 600 feet, and the depth at low water 18 feet.

On the Avon, a short distance below Bristol docks, there were, until a few years ago, two reverse curves close together, having a radius of 600 feet. The rocks have since been cut away, and the radius increased to 1500 and 2500 feet. The

horseshoe bend lower down this river has two curves in a distance of about $1\frac{1}{4}$ miles, the radius of one being 858 feet, and of the other 1980 feet, the low-water width of the channel at this spot being 264 feet. Large steamers get round these curves, but with difficulty.

The curve at Swinefleet, on the river Ouse, until recently had a curve of 1188 feet. Owing to the great run of tide at this part of the river, from 5 to 6 knots, this curve was found to give trouble to the steamers going up to Goole docks, the largest of which were about 1500 tons. The radius of this curve has now been increased to 1683 feet, with a channel 750 feet wide at low water.

In the Witham the New Cut is curved to a radius of 8500 feet, with a low-water width of 200 feet, and no difficulty is found in lighting this channel or navigating with steamers of 3000 tons capacity. A short distance below the entrance to the Boston dock the river has a bend, having a curve of 1056 feet and a width of only 120 feet. Large steamers pass round this bend, but care has to be exercised when doing so.

On the Seine, between the estuary and Rouen, there are ten principal curves, five of which describe nearly 180 degrees. The smallest radius of these curves is 6562 feet, but, owing to the width of the navigable channel varying from 300 to 1100 feet, they do not seriously impede the navigation. The curve at Tancarville, in the trained portion of the channel, has a radius of 8200 feet. This is considered to be less than it should be at this point, as the currents here attain a velocity of over 8 feet a second, causing violent eddies, troublesome for the navigation and unfavourable to the transmission of the tides.

On the Garonne, just above the junction with the Gironde, there is a curve of 17,160 feet radius, followed by one of 10,560 feet; and immediately below Bordeaux one of 3300 feet.

The Scheldt, a short distance below Antwerp, has a curve of 1250 feet radius, and two other curves between there and Lillo nearly as sharp.

The Weser has five curves between Bremen and its mouth, the sharpest of which has a radius of 4166 feet, with a low-water width of 262 feet.

The smallest curve on the Suez Canal has a radius of 3500 feet.

On the Danube, in the Sulina Channel, curves of 800-feet radius were found unworkable, and those of 1200 feet gave

trouble to the longest steamers passing through the channel. The sharper curves were therefore increased to 1600 feet radius, with a low-water width of 370 feet.

On the North Sea and Baltic Canal, now in process of construction, and which is intended for the navigation of vessels of the largest class, the radius of the curves ranges from 3281 to 19,686 feet, and averages 9309 feet. In curves under 8202 feet radius the navigable width is increased from 118 to 170 feet. Where two counter-curves occur, a straight line has been interpolated. About thirty-seven per cent. of the canal consists of curves.

If a vessel has little water to spare under her keel, it renders the navigation of curves more difficult, she being, under such conditions, more slow in answering her helm.

Effect of Deepening and Improving.—The effect of deepening and improving rivers is to increase the range of the tide and the volume of tidal water passing up and down the channel. For example, in the Thames, the waterway of old London Bridge was so restricted that the sectional area of the water through the arches was less than half that of the channel of the river, causing the flood tide to be 6 inches higher on the lower than the upper side, and the ebb to be from 3 to 5 feet higher on the upper than the lower side. The removal of this obstruction, the dredging away of shoals at Blackwall, Dagenham, and other places in the lower reaches, over several of which the low water had only half its normal depth, and the removal of about a million cubic yards of gravel and sand between London Bridge and Vauxhall, has resulted in accelerating the time of high water at London Bridge about half an hour, in lowering the low-water line nearly 4 feet at London Bridge and 2 feet at Teddington, and in raising the line of high water between those places upwards of 6 inches, and increasing the tidal volume in this reach twenty-five per cent.

On the Tyne, the result of the dredging and improvements made in the channel resulted in lowering the low-water line 6 feet at Blaydon, 15 miles from the sea, and 3 feet 6 inches at Newcastle; and raising the line of high water at the same places 1 foot, giving an increased range of 7 feet and 4 feet 6 inches respectively, and adding about 20 million cubic yards to the tidal volume at spring tides. The time of high water has been advanced three-quarters of an hour, and the first of flood

now reaches Newcastle from Shields in fifteen minutes as against two hours and a quarter formerly, thus increasing the velocity of the tidal wave from 4¼ miles an hour to 38 miles.

On the Clyde, the low-water line has been depressed 8 feet at Glasgow, and the high-water raised 10 inches, making a greater range of tide of 8 feet 10 inches. The time of high water, as compared with that at Port Glasgow, 17½ miles below, has been advanced three-quarters of an hour since 1835, and three hours since the beginning of the present century. The first of the flood now reaches Glasgow in about an hour and a half after leaving Garmoyle Light, or at the rate of 9 miles an hour. Spring tides range about 11 feet 2 inches at Glasgow, and rise 1 foot 2 inches to 1 foot 6 inches higher there than at Port Glasgow, and ebb out 4 to 9 inches lower, making the range 1 foot 6 inches greater at Glasgow.

On the Seine, the low-water has been depressed in the river 2 feet 6 inches, the high-water line remaining the same, and is level with that in the estuary. The first of the flood reaches Rouen an hour earlier than before the improvements were made. The tidal wave of the first of the flood travels from Honfleur to Rouen at a rate varying from 7 to 25 miles an hour, the greatest rate being over a portion of the river which is 20 feet deep at low water. The results would, no doubt, be greater in this river if the tidal water had a free access into the channel.

The removal of the shoals in the Tay between Newburgh and Perth depressed the low-water line, and caused the tide to reach Perth an hour sooner, but did not affect the level of high water. So also the removal of the old Cross Keys Bridge across the Nene caused a depression in the low water of 2 feet 3 inches, but the level of high water remained the same.

NOTE.—After this chapter was in print, the author's attention was drawn to an incident which occurred in the Garonne, as given in M. Partiot's book, "Étude sur les Riviéres a Marées." A steamer was sunk at the mouth of the river Gironde, opposite Verdon, by a collision, and rested on her keel at the bottom of the channel, the masts and chimney only showing at low water. On an examination being made by the agents of the salvors, it was found that the vessel was completely buried in sand, the sandbank extending about 100 yards fore and aft of the vessel, and 50 yards from each side. Subsequently, on a second examination being made, it was found that the sand had disappeared, and the channel was so scoured out that chains could be passed under the keel of the vessel at either end, the hull being supported only in the middle. The first examination had been made at the end of the ebb, while the second was made at the end of the flood. Soundings were then taken at every hour during a complete tide, when it was found that during this interval the vessel was alternately covered and uncovered with sand. The ebb deposited the sandbank, and the flood removed it again.

CHAPTER VII.

BARS AT THE MOUTHS OF TIDAL RIVERS, AND LITTORAL DRIFT.

IN a paper contributed to the *Proceedings of the Institution of Civil Engineers* in 1890, the author divided bars into four classes.*

1. Those consisting of hard material not affected by the scour of the current.

2. Those due to the deposit of alluvial matter brought down by rivers draining large areas of country, and discharging into tideless seas, or where the rise of tide is very small.

3. Casual bars of shingle or sand, occasionally heaped up by the action of the waves in heavy gales, and afterwards displaced by the currents.

4. Bars consisting of sand or shingle, which, while permanently retaining their general features, are constantly subject to alteration from effects caused by winds, waves, and varying currents.

To this arrangement it is intended to adhere in this chapter.

A bar across a tidal river may be described as consisting of one or more banks or ridges extending across the entrance channel, having deeper water both on the seaward and inner sides, and the crest rising above the general level of the bottom of the channel adjacent. In non-tidal rivers the bar consists of a long flat shoal at the mouth of the river, which rises so far above the general level of the bottom of the river, both at the outfall and in the channel above the shoals, as to render the channel useless for that class of navigation for which otherwise it would be fitted.

Bars are not common to all rivers. At the mouths of most estuaries with sandy bottoms ridges and depressions similar to

* "Bars at the Mouths of Tidal Estuaries," by W. H. Wheeler, *Min. Proc. I. C. E.*, vol. C.

bars are to be found, but in many cases, owing to the great depth of water over them, they cannot be deemed bars. In other estuaries where well-defined bars exist, the crests of these do not rise above the general level of the channel inside, and therefore do not form impediments to vessels going up or down the channel. The approaches to the Thames, the Humber, the Forth, the Severn, and the Scheldt, are all encumbered with large beds of sand, through which the tidal currents always maintain one deep low-water channel free from the obstruction of a bar. The entrance to the Seine has its bottom furrowed by ridges, which rise from 1 to 2 fathoms above the hollows, but as there is from 6 to 7 fathoms on the crest of these ridges, the general depth being about 7 fathoms, they cannot be considered as bars.

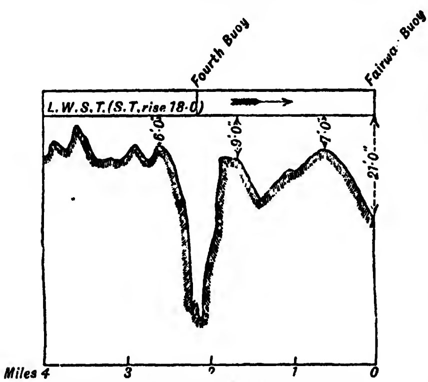


FIG. 13.—Section of bar of River Tees.

On the Tees, previous to the training works immediately outside the bar, the depth, as shown in Fig. 13, was 21 feet at low-water spring tides, on the bar there were 7 feet, and inside 30 feet. At 1 mile above the bar the water shoaled to 9 feet, at 2 miles to 6 feet, the navigable depth continuing to shoal above this. In this case, therefore, the bar was not the impediment which prevented vessels from getting up the river, although, no doubt, it was a source of danger to vessels trying to cross it in rough weather without having a sufficient depth of water under them.

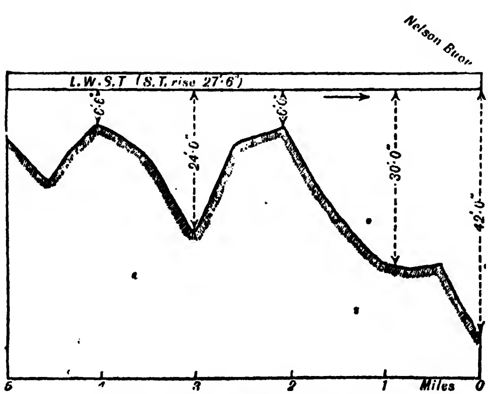


FIG. 14.—Section of bar of River Ribble.

The bar which exists on the Ribble (Fig. 14), which has a depth at low water of about a fathom on the crest, with 5 fathoms on the sea side

and 4 on the inner side, cannot be considered as an impediment to the navigation, as the channel above it has a less depth for some distance than is found on the crest of the bar.

The bar which formerly existed on the Tyne (Fig. 15) had a fathom on it at low water, with 9 fathoms on the sea side and 2 on the inside. The river immediately above Shields harbour had only from 4 to 6 feet. In this case, although the bar might not be the cause of preventing vessels of deep draught navigating the river, yet it was a hindrance to navigation, as inside the bar there was a deep pool varying in depth from 23 to 10 feet at low water, in which vessels, although unable to navigate the river at low water, could yet lie afloat at moorings waiting for a favourable tide or weather. The bar prevented these vessels from proceeding to sea at low water, which otherwise they could have done.

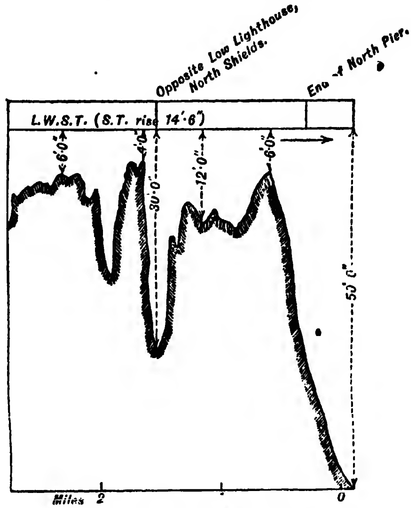


FIG. 15.—Section of bar of River Tyne.

Bars composed of Hard Material.—Bars of the first class consist of a shelf or ridge running across a river-mouth, consisting either of stone, very hard clay, or occasionally of large boulders, or shingle cemented together with clay. Such bars can only be removed by dredging. The effect of the removal may be permanent, or the surrounding conditions may be such that the hard material may be replaced by sand, and the bar reappear. An example of this was quoted, in the paper referred to, by Mr. Smith. At Aberdeen harbour, a bar consisting of boulder clay was removed from the entrance channel by dredging. After the removal of the clay a bar formed again, and continued to do so as often as dredged away, by the piling up of heavy sea-sand driven in by the waves during storms. By continual dredging the supply of sand overlying the beach of boulder clay was at last exhausted, and a permanent improvement obtained

by extending the deepening in continuation of the line of channel outwards for nearly half a mile to the 5-fathom line.

The bar across the mouth of Lough Carlingford, on the east coast of Ireland, is another example of this class. It consisted of hard clay mixed with stones, some of which weighed as much as 4 tons. Through this bar a channel 400 feet wide, with a depth of from 14 to 18 feet at low water, was dredged. In this case the result was permanent, and there was not any reforming of a new bar.

The Tay is encumbered with an inner bar, about 6 miles above the outer bar, consisting of boulders and hard gravel so heavy and compact as to be uninfluenced by the currents. The crest is 4 feet above that of the outer bar.

Bars due to the Deposit of Alluvial Matter.—These are to be found in tideless rivers, or where the rise and fall of the tide is so small as practically to render the river non-tidal. Numerous instances of such bars occur at the mouths of the rivers discharging into the Mediterranean, or the bays along its coast, and in those discharging into the Gulf of Mexico, in both of which cases the rise of tide is less than 2 feet; and also in the Black and Caspian seas, which are tideless.

In tidal rivers, the ceaseless action of the tides, by which an enormous volume of water is poured into and discharged from the river twice every day, not only serves to keep the alluvial matter contained in the water in suspension, but, by diffusing it throughout the whole volume of the tidal water brought in on the flood, carries the greater part of it away on the ebb and deposits it in the deep water of the ocean. In a non-tidal river the alluvial matter brought down the channel continuously, and to a very much increased extent in floods, settles at the mouth of the river, where the current is checked and the velocity is reduced. In time large deltas are thus formed, through which the water from the river finds its way to sea by several shallow channels.

The Tiber and the Po are both illustrations of the incapacity of non-tidal rivers to maintain their outfalls, the beds of these rivers being so much raised that they are above the level of the country through which they pass. The Rhone, which flows through a channel having a depth of 40 feet at ordinary seasons, and discharges into the Gulf of Foz in the Mediterranean, is encumbered at its mouth by a bar, over which there is only a depth

of 6 feet. This short length of shoal or bar entirely deprives this river, in its natural condition, of the enormous advantages which it possesses as a navigable inland stream. The Nile is another illustration of a river which, emptying into the almost tideless Mediterranean, has not water enough at its mouth to enable it to be navigated. The Mississippi and several other large rivers discharging into the Gulf of Mexico, have deltas or bars at their mouths. These bars prevented the use of the rivers in their natural condition for such navigation, as otherwise they are eminently adapted. The example of the Danube discharging into the Black Sea is too well known to require further notice. The Volga, which, with its tributaries, has a navigable waterway of about 7500 miles, is yet so encumbered with a long bar at its mouth, where it enters the tideless waters of the Caspian, that there is barely 8 feet of water.

In all these cases the rivers have formed deltas by the deposit of the alluvial matter brought down by the stream, which has been deposited owing to a diminution of the velocity of the current, and to eddies produced by the outpouring water coming in contact with the littoral currents.

The large accumulations of sand found in most tidal estuaries vary considerably both in their composition and cause of deposit from alluvial deltas, and also in the fact that they are in situations where there is generally a considerable rise of tide. These sands are not continually accreting and forming deposits, but maintain their original form and extent in a more or less stable state so long as the natural conditions under which they exist remain unaltered. In the more open sea the accumulations of sand may be drifted along the coast during long-continued gales and form casual bars at the mouths of the rivers, but this material will be transported away when the normal conditions are resumed. For example, on the coast on the south side of the Straits of Dover there are large masses of sand which, reaching from the north-east past Ostend and Dunkirk, extend southward past Calais and Boulogne. A strong gale from the north-east causes the sea to be so rough that the sand stirred up by the waves is drifted and deposited in the comparatively slack water near the harbours, forming bars across their mouths which rise several feet above the general level of the bottom of the sea. These bars remain until gradually dispersed by the action of the waves during westerly gales. After a gale lasting three

days, the quantity of sand deposited at the end of the pier at Dunkirk was estimated by M. Plocq, the engineer, at 40,000 cubic yards.

It is unnecessary to multiply further examples.

Bars at the Mouths of Sandy Estuaries.—This form of bar is the type most frequently met with. They possess features of a most remarkable character, consisting of one or more ridges or mounds of material, the particles of which have not the slightest coherence, yet stand with a slope much steeper than their natural angle of repose. Rising in some cases as much as from 40 to 50 feet above the bottom, they maintain their positions across channels subject to a tidal rise of from 20 to 30 feet, through which currents run at a rate of from 3 to 4 knots, and the direction of which is reversed four times every day. Exposed to the storms and waves of the open sea, they are sometimes partly dispersed or added to, altering their position and shape, yet having a normal condition to which they are restored when the disturbing causes cease.

The most remarkable example of a bar of this class is that of the Mersey (Fig. 16). The bar extends in a horseshoe shape

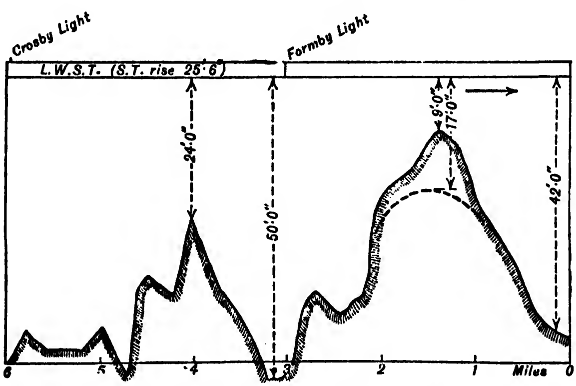
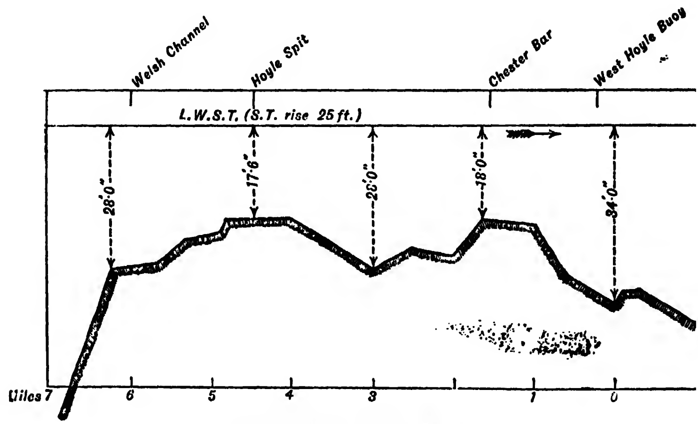


FIG. 16.—Section of bar of River Mersey.

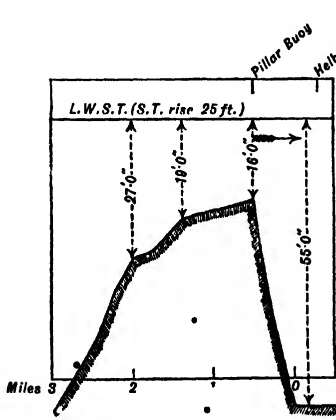
across the channel, which is here a mile wide, a short distance above where it joins the open sea, from a mass of sandbanks on either side. Its length is about three-quarters of a mile, and on its crest at low water the depth varied from 7 to 15 feet, while in the channel on the inside there is a depth of about 8 to 9 fathoms, and on the sea side of 7 fathoms. During the last 50 years the low-water channel of the Mersey has altered its

position three times, yet every new channel has been accompanied by a bar of sand across it, notwithstanding that the low water on the inside runs through a deep rocky channel having a depth of from 30 to 50 feet, and the range of tide in high spring tides is 30 feet.

The river Dee, which discharges on the same part of the coast as the Mersey, has two outlets into Liverpool Bay, both of which have sandbars. In the Welsh Channel there are two



Section through Welsh channel.



Section through Helbre Swash.

FIG. 17.—Sections of bars of River Dee.

bars, having about 18 feet on their crests at low water, and 28 feet between them, deepening at the sea end to 34 feet, and on the inside to 28 feet, and at a little distance above to a deep

hole having from 9 to 10 fathoms. The bar of the channel by the Helbre Swash has 16 feet on its crest at low water, and 55 feet on the outside, and 27 feet on the inside, also deepening in one place to 8 and 9 fathoms (Fig. 17).

The bar at the mouth of Boston Deeps (Fig. 18) is a type of a rather different character. The Wash, on the east coast, is divided into two parts at low water by a long narrow bank of sand, which extends for 15 miles between the two channels. The sides of this sand at the lower end are so steep as to be nearly vertical, there being a depth of over 3 fathoms at low water close up to the sand. Lynn Deeps, on the south side, is 7 miles wide at the mouth, and has a depth of from 13 to 15 fathoms at low water spring tide. Boston Deeps, on the north side, is only a quarter

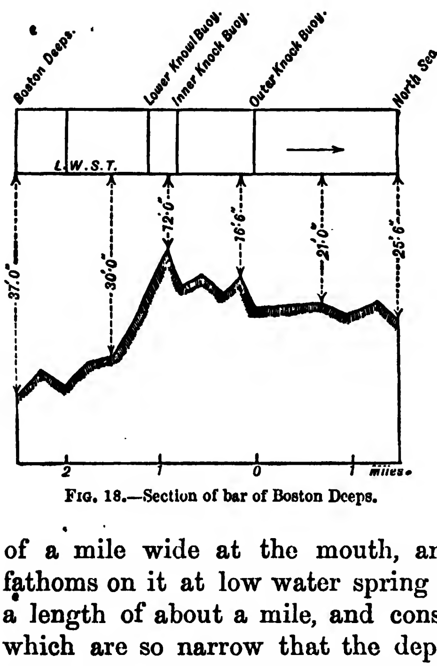


FIG. 18.—Section of bar of Boston Deeps.

of a mile wide at the mouth, and has a bar with only 2 fathoms on it at low water spring tide. This bar extends over a length of about a mile, and consists of three ridges of sand, which are so narrow that the depth of water within a single cast of the lead varies a fathom. Spring tides rise 23 feet and set over the bar. The channel shoals from 5 fathoms on the inside to 2 fathoms on the bar, and then deepens to 4¼ fathoms outside. The ridges, although continually altering their form, maintain a general uniformity.

Bars, although retaining their character as bars, may yet alter their position due to gales and other causes. Thus the sandbar which formed inside the north pier of Aberdeen, where the exposure is north to north-east, was driven up the harbour during heavy weather and strong gales from the north-east. If there happened to be a dry season, and the ebb current slackened, it was driven further up the harbour; but in calm weather and with heavy freshets inside, it was shifted down nearer the sea. At the small harbour of Valery-en-Caux there is a continual

travel of shingle across the entrance from the west, but under ordinary conditions the tidal flow is able to maintain a channel. When, however, there is a long continuance of westerly winds, the entrance is sometimes completely closed, and an opening through it has to be made by manual labour. When strong easterly gales blow for any length of time, the surf drives the shingle from the entrance, lowering the bar and clearing the channel. The collection of shingle here is assisted by an eddy current called the sciade, formed by the flood-tide, which swirls round the pier-heads and is increased in force when the movement of shingle is greatest during westerly winds.

The shingle-bars on the south-east coast frequently alter their position due to gales. Thus at Lowestoft, if the wind continues for a long time from the north-east, the shingle accumulates across the mouth of the harbour to an extent that considerably detracts from the depth of the channel. At Southwold north-east winds increase the height of the bar, sometimes to such an extent as to leave it dry at low water, and when the winds are from the opposite direction, leaving several feet of water over it. Both at Orford Haven and at the mouth of the Deben the shape and position of the bars are continually changing.

Formation of Sandbars.—A tidal bar assumes the form of a ridge, having deep water on either side. The ridge, being once formed, aids in its own maintenance. As already pointed out, sand is moved in an estuary in a series of ripples or ridges, having a long slope on the upper side, or that from which the current is coming, and a steep face on the down side. Over this steep face, or tip, the particles of sand are rolled. In a

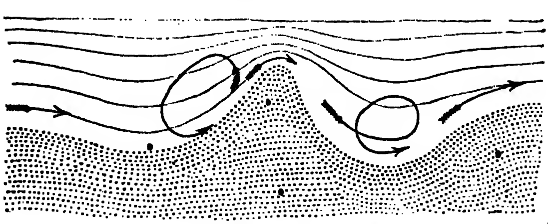


FIG. 19.—Diagram of Sandbar.

tidal channel where the current is continually being reversed, the position of this face varies with the direction of the tide. At the foot of the ridge a rotary or screwing motion is set up,

which whirls the particles of material round the bottom of the hollow, continually tending to scour it deeper. The current, moving forward along the bottom, is deflected upwards, and rolls the particles up and over the ridge as shown in the illustration (Fig. 19). The motion of the sand as here described may be distinctly seen in the working model of a tidal estuary hereafter described.

Channels where Bars are absent.—Bars having been once formed and subsequently maintained by the action set up by their shape, if removed by dredging, are not liable to be reformed, unless in situations where there is a strong littoral drift and the ebb current is not sufficient to keep this out of the channel. The conditions most favourable to the absence of bars are those where the estuary assumes a funnel-shaped form, decreasing in width and depth from the mouth upwards; when the momentum of the tide is not unduly checked; when there is a free propagation and long tidal run; when the ebb current is so directed as to have a preponderating force over the flood in the removal of material; and when the outfall channel is continued into deep water.

Theories as to the Cause of Bars.—It has been maintained that bars are due to the detritus carried in suspension by a river when it enters the sea, either from the slackening of the velocity of the current owing to increased area; or to the meeting of two currents which neutralize each other; or to the effect of the inflowing tidal water, which, from its specific gravity being greater than that of fresh water, checks the lower stratum of the ebb current and causes deposit; also to a conflict caused by the meeting of the flood and ebb currents; and to an insufficiency of back water.

With regard to the first theory, this is so, as already pointed out, in non-tidal rivers. In a tidal river, where the current is continually being reversed, the particles of matter brought down in suspension from the upper reaches of a river are too light to form a bar, but remain diffused amongst the tidal water until deposited in the sea. The material of which tidal bars are formed consists of shingle or sand, the particles of which are too large and too heavy to remain in suspension.

As to bars being formed by the conflict caused by the meeting of the ebb and flood currents, and that the bar is the nodal point where this conflict takes place, and that at this place the

matter in suspension is deposited, the answer is that there is no one defined place where the action of the tidal currents is reversed, but this position varies with the condition of the tides, whether spring or neap; and as the matter in suspension is not that of which bars are composed, if such a nodal point existed, it would not be the cause of the bar. The continued reversal of the current has, no doubt, a material effect in maintaining the bar, but is not the cause.

The theory that attributes bars to the conflict occasioned by the meeting of the fresh and salt waters seems disposed of by the fact that, while the bar remains practically in the same position, the point where the fresh and salt waters meet varies with every tide and the amount of fresh water coming down the river.

Importance has been attached to the volume of fresh water coming down a river as affecting bars. Where the estuary is small as compared with the magnitude of the river, and the bar near to its mouth, land floods may increase the depth over the bar, even at high water, and also the scouring action. Thus, in the Yare at Yarmouth, in heavy land floods the depth of the water over the bar at low water is as great as at ordinary spring tides. In the Ganges, although the rise of tide is as much as 17 feet, yet the volume of water discharged in floods is so enormous as to override the tidal wave, and at such times the downward flow never ceases. The bar at the mouth of the Douro is considerably improved by land floods, which are exceptionally heavy at times, being 1500 times as great in volume as the ordinary flow. The outfall of this river is protected by a wall which runs out on the north side. The detritus drifted along the coast accumulates at the end of this wall and forms the bar, the depth of water on which varies from 14 to 17 feet. The rise of spring tides is about 11 feet, whereas heavy land floods have been known to rise more than 33 feet, and have been reported as running down the channel at the rate of 16 knots—a velocity which, however, probably has been over-estimated. The discharge of the fresh water during these floods is twenty-eight times as great as the tidal water at spring tides (*Min. Proc. I.C.E.*, vol. lvii.).

The bulk of the material brought down by land floods in tidal rivers which are navigable, as distinguished from mountain torrents, is of an alluvial character, and remains in suspension as

long as the water is in motion. There is, however, a certain proportion of sand which, in a heavy flood, may be carried to the bar, and for a time add to it; but the probability is that in such a case there would be an increase in the volume and force of the ebb sufficient to carry these particles over the crest and out to sea. In heavy land floods, material may also be washed out of the upper part of an estuary, and be carried down to the bar and remain there. An example of this is afforded by the Mersey. The upper estuary of this river consists of a large area of sand, deposited there like other similar beds, when the river and estuary received its present form. Additional sand and detritus is brought down by the river in floods, and supplied from the erosion of the cliffs. Material is also carried out of it by heavy floods and the ebb current, so that the area and amount of material in the estuary is kept at a normal quantity. Periodical surveys indicate that at times it increases and at others decreases, but over a long period of time it retains its original features. This is a condition common to most sandy estuaries. Whenever there have been heavy and long-continued freshets down the Irwell and the Mersey, the course of the channels through the estuary has been changed and the sand disturbed. The ebb has been sufficiently powerful to carry a certain quantity of this sand down to the bar, but not to lift it all over the crest. Under these conditions, it has been found that after heavy freshets the bar has increased, in height, and the depth of water over it decreased. On the resumption of the normal flow it has gradually deepened again, but had not, up to the time when the present dredging operations began, recovered the effect of the last long-continued rains which occurred for several years in succession, and when it was estimated that nearly 6 million cubic yards had been transported from the estuary. The heights on the bar, and further details as to this estuary, will be found in the description of the river Mersey given afterwards.

Generally, in tidal rivers, the size of the estuary is such that the land water bears a very small proportion to that of the tidal water. The fresh water coming into an estuary at its upper end in floods takes up space that under normal conditions would be occupied by water brought in by the tide. The supply of tidal water, being unlimited, fills the space available for it to occupy; if any portion of this space is occupied by fresh water,

there is so much less room for the tidal water. The fresh-water level is raised and driven back up the river, but the level of high water in the lower part of the tidal estuaries of this country, with few exceptions, remains unaltered during the heaviest land floods. The river may be incapable of discharging the fresh water brought down, causing its banks to overflow and the country to be flooded; but while this is occurring in the upper part of the river, the level of high water in the estuary may only attain the height due to ordinary tidal action. So far as the channel is confined, the volume and depth of the latter part of the ebb will be greater than under normal conditions; but when the fresh water enters the open estuary, the quantity discharged is so small as compared to the volume of the tidal water, that the quantity passing out over the bar will be practically the same whether freshets prevail or not.

The fact that a bar remains permanently, and that land floods are intermittent, disposes of the theory that they are the governing factor in maintaining the outfall.

It cannot with reason be said that the smallness of the watershed of the Mersey, which drains only 1706 square miles, is the cause of its bar. The volume of tidal water flowing through its channel continuously is calculated to be 500 million cubic yards each tide, as compared to 2 million cubic yards due to occasional land floods. The total quantity of tidal water which passes and repasses over the sandbanks between New Brighton and Formby Point is 1520 million cubic yards. Nor can the bar of the Tay be ascribed to a deficiency of fresh water, this river having the greatest discharge for its drainage area of any river in Great Britain, and almost equal to the Thames; yet the quantity of tidal water was estimated by Mr. Stevenson to be forty times as great as that of the freshets. In a large river like the Thames, it would be difficult to prove that the absence of a bar was due to the ordinary fresh-water flow, or to occasional land floods, when the quantity of water flowing even as high up as between Teddington and Gravesend is nine times as great as that due to the freshets in heavy land floods; or in the Humber, where the discharge in heavy freshets is only about one-eighth of the tidal flow. This river also affords evidence against the theory that bars are due to material brought down the stream, as no river in this country carries so large an amount of alluvial matter in suspension as the tributaries of the

Humber. It is unnecessary to give other instances, as this matter has already been fully dealt with.

There are bars at the mouths of channels in estuaries situated so far from the river that it is impossible that they can be caused by fresh-water deposits. The bar at the entrance to Boston Deeps may be taken as an example. It is situated 20 miles away from the mouths of the two rivers which discharge into this part of the estuary. The quantity of fresh water is so small as compared to the tidal volume that it becomes diffused amongst it, and any influence is lost a long distance above the bar. The material brought down in suspension is deposited on the shores of the coast, the growth of the salt marshes being sufficient to account for the quantity of alluvial matter brought down. The bar of Dornoch Firth is also another instance. The bar of this river, as described by Mr. Stevenson, is formed of pure sand, and is situated 14 miles seaward of the point where the river Oykell enters the estuary. The magnitude of the firth as compared to the river, the high-water area at Whitness Point being fifty times greater than at Bourn Bridge, precludes the formation of this bar from being due to the small quantity of detritus brought down by the river.

The subject as to the formation of bars was thoroughly discussed at the Institution of Civil Engineers, the almost unanimous opinion of the engineers, both English and foreign, who took part in the debate so entirely accorded with the views set forth in the paper laid before the Institution by the author, that these may be taken as mainly correct.

The existence of tidal bars is due to the action of the sea, and not to that of the land water. And the chief factors in their maintenance are tidal currents and on-shore gales.

For their formation, it is necessary that the bed of the estuary and of the adjacent sea should consist of sand or shingle; and that the depth of water should be sufficiently shallow to allow of the action of waves and tidal currents on the bed.

Bars owe their origin and existence to the balance of forces, which was established when the coast-line and estuary assumed their original form. These are forces which have continued to operate ever since, and which tend to build up or disperse them. The balance of forces originally set up, however, still continues.

On coasts where there is a travel of material along the shore, it is drifted in its course across the opening in the coast-line

which forms the outlet for the river. The flood tide, setting through this opening into the estuary, tends to carry the material with it; the ebb tide, on the other hand, tends to carry it back and disperse it into the deep water of the sea.

Wherever there is any considerable motion of the water where the bottom of the sea is mobile, the material invariably lies in ridges, these in some cases being of considerable height. Bars may therefore exist across the mouths of rivers where there is no drift along the shore, the sand being thrown up and assuming the form of a ridge or ridges, and thus forming a bar by the action of the wind, waves, and the tidal current, and being maintained by the action which its form sets up.

Bars may also exist in situations off the coast where no river intervenes. One instance of this is found in the English Channel off Portland Bill. The beach here is steep and covered with shingle; the tide sets with great force, and at a velocity at the rate of 5 to 7 knots, round the projection known as the Bill, causing tremendous whirls and eddies. At some distance from the shore is a succession of pebble ridges, varying in height from 5 to 9 fathoms, forming the bar to the bay. With northerly winds the distance of these ridges may be 2 miles from the shore, with overfalls beyond that distance, and with southerly winds they scarcely exceed half a mile from the Bill, the depth of the water being from 10 to 20 fathoms at low water.

Where the water at the mouth of a river is shallow, and the quantity of material being moved along the shore great, the effect may be to form such a continued bar across the outfall as to divert it entirely from its original course. In this case the balance of forces has been disturbed. Examples of this case are to be found in the Yare, on the Norfolk coast (Fig. 20), where the travelling sand and shingle has driven the mouth of the river nearly three miles from its original course. Also in the small rivers Alde and Ore, lower down on the same coast (Fig. 21), which approach within 73 yards of the sea near Aldborough, and there have been deflected

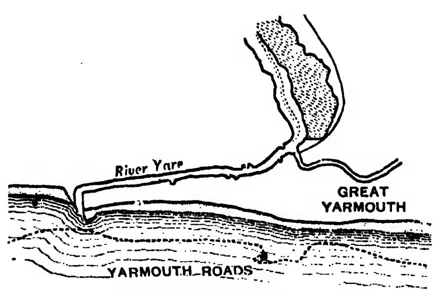


FIG. 20.—Plan of River Yare.

by the travelling shingle abruptly south-west, and, after running parallel with the coast, finally find an opening into the sea 9 miles lower down. In many parts the new channel is separated from the sea by a ridge in places only about 70 or 80 yards wide; and maintains a depth throughout at low water varying from 12 to 30 feet, the bar at the entrance having 9 feet.

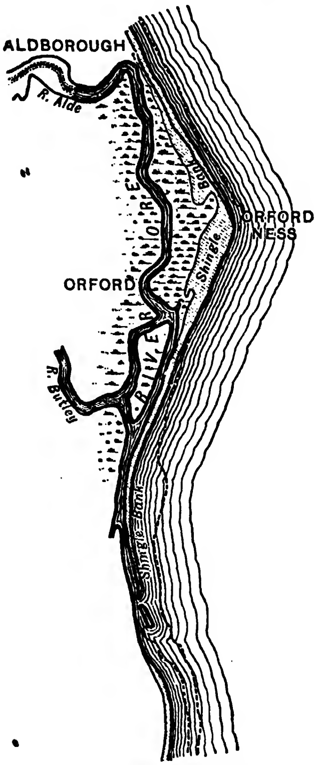


Fig. 21.—Plan of River Alde.

The Adur, on the Sussex coast, is another example. The shingle, moving along the beach, has forced the outfall 4 miles eastward. In all these cases the direction of movement coincides with the direction of the flood tide, and is most active with those gales which have the most effect in producing high tides.

Effect of Contour of Coast-line on Formation of Bars.—Where the bed of the ocean deepens rapidly away from the mouth of the estuary, the particles of material moving along the coast are less easily carried into the channel by the flood, and are more readily transported from it by the ebb. It is not to be expected, therefore, that bars will be found in such situations.

Deep bights, gradually increasing in width and depth towards the ocean, are unfavourable to the formation of bars. On the other hand, an estuary which has its connection with the sea on a low flat coast at right angles to the direction of the tidal current in the ocean, is disadvantageously placed for keeping its entrance clear. The difficulty is further increased when the water has to find its way to sea across a beach encumbered with sand, as is the case all along the east side of the Irish channel, where the tidal currents have continually to contend with an immense mass of moving material, liable to be displaced at every gale.

A shallow bay, in which the tide runs more slack than in

the offing, is almost always productive of a bar at the mouth of an estuary having its connection at its head. An example of this was afforded by the Tees in its natural condition. The estuary of this river discharges into a shallow bay on the east coast, in which a sandbank, having only from 3 to 7 feet of water over it at low water spring tides, existed previously to the breakwaters and training walls being constructed.

A prominent projection of the coast-line on the side from which the flood tide comes, causes the current to run round it with sufficient velocity to prevent the deposit or continuance of material at the mouth. Such is the case with the Humber. The tide setting from the north flows round Spurn Point into the estuary at the rate of 4 knots, and maintains a navigable channel 3 miles wide and three fathoms deep, the lower side of the entrance consisting of a large area of sandbanks. In the Tay, however, the outfall of which is situated at the head of a bight, having from 6 to 7 fathoms close in shore, and which has a prominent projection of the coast-line known as Buddan Ness on the side from which the tides set, is encumbered with sand-beds which extend out into the bay from 2 to 3 miles, and there is a well-developed sandbar. The tidal flow is, however, impeded in its course into the estuary by a hard ridge, which is not amenable to scour.

In the Firth of Forth, where there is no bar, the coast-line on the south side projects nearly 15 miles beyond that on the north, from which the direction of the flood sets. The estuary is trumpet-shaped, the deepest water, 27 fathoms, being in the centre, and shallowing to about 12 where the estuary widens out.

The estuaries of the Thames and Lynn Well, neither of which is encumbered by a bar, have projecting coast-lines on the lower or opposite side to the direction from which the tide comes. The outfall of the Seine is situated in the bight of a bay having a considerable projection on the east or opposite side to the direction of the set of the tide, past which it runs with considerable velocity across the mouth of the estuary. The Scheldt discharges on a low flat coast, where the rise and fall of the tide is small. The Shannon and the Bristol Channel have each natural projections which guide the tide directly into their estuaries, which gradually decrease in width. None of these estuaries have bars.

Littoral Drift.—The drift of material along the shore is almost

invariably in the same direction as the set of the flood current. Gales which blow in the same direction as the set of the flood, or rather gales blowing obliquely on shore and acting with the flood current, raise the largest tides and the largest waves; and consequently cause the greatest amount of erosion on the cliffs, and provide the greatest quantity of material for drift. The maximum of effect of erosion and disturbance is at a high spring tide, with heavy on-shore gales.

The material broken up from the beach or eroded from the cliffs is incessantly rolled about until the pieces become diminished in size from broken masses of rock or large flints released from the chalk cliffs to pebbles, gradually decreasing in size till the state of coarse and then fine sand is reached. These materials are assorted by the action of the sea according to their size and specific gravity. The large pebbles are carried the highest up the beach, the coarser particles of sand and shells form the lower part. When the shore is composed of shingle, the sand will be generally found beneath low-water mark. The finest particles of sand, when extended over a sufficiently wide range to be acted on by the wind, are frequently lifted up and carried along to the shore and inland, forming large sandhills or dunes, which sometimes rise to a height of 50 to 60 feet. In travelling along a beach, the smallest pebbles advance more rapidly and to greater distances than those that are larger, until at some distance from the source of supply sand only will be found.

Although under certain conditions on-shore gales drive up detritus and cause it to accumulate on a beach or across a river mouth, under other conditions it may be the means of denuding the beach and deepening the coast-line.

Ground swells also operate in denuding beaches. These are due to waves generated in the open sea and breaking at right angles to the shore-line. As the crest of a wave rolls towards the shore or into a bay, its trough comes in contact with the bottom. The upper part of the wave continues its forward motion, and thus throws forward a large volume of water, which, running up the beach as a surface current, returns as an under current, and carries back with it the sand and stones loosened by the breaking wave. In its reflex action it therefore sucks out the material from the beach, and in time leaves it denuded. It is by this action that many tidal harbours are kept open.

On-shore gales during ebb tides sometimes act in the same manner.

It is a matter of common observation that, as the tide recedes from a beach, there is left behind at the level of high water, or frequently a little above it, a line of "wrack," or collection of material consisting of pieces of wood, seaweed, shells, and, where shingle is present, pebbles, some often of considerable size, and that this takes place even in the calmest weather, when there are no waves except those due to tidal influence.

Careful observation will further show that this *débris*, shells, and shingle travel along the coast, the direction of movement being obliquely to the shore, but in the direction of the flood tide.

In the transport of this littoral drift, the flood is, then, the preponderating force. On the turn of the tide, the ebb sets in at first during slack water, and gradually subsides from the highest level of the tide without creating a sensible current. It is, therefore, incapable of carrying back the material pushed by the flood to the highest point reached by the tide, which remains there until the succeeding flood tide again pushes it onward. The illustration in Fig. 22 approximately represents the three forces at work.

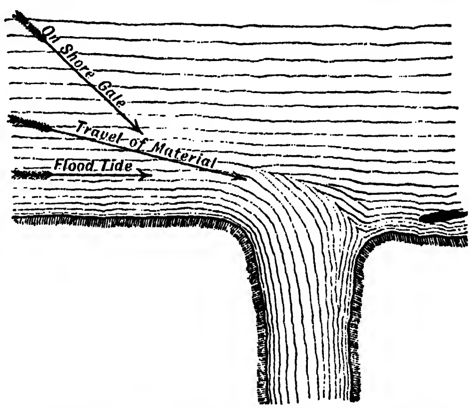


FIG. 22.—Diagram showing movement of littoral drift.

Without consideration it is difficult to realize the fact that pebbles of considerable size are thus moved upwards and along the beach by a movement of the water of such small velocity that, in a running stream, it would be quite incapable of even moving them.

The tidal wave is, however, a great moving force capable of transmitting its power to objects with which it comes in contact. As it rolls shoreward from the great depths of the sea with a vast momentum, it is checked on reaching the shallow water by the rising beach, and imparts a portion of its energy

to any pebble or other obstruction with which it comes in contact. The pebble, being water-borne, is easily transported onward; and step by step is raised to the highest point touched by the trough of the wave. The largest pebbles are carried the highest, because, owing to their size and weight, they receive and retain the greater amount of momentum, and, once deposited, become as it were anchored, whereas lighter substances are carried back by the receding wave.

It has generally been received as an axiom that the movement of littoral drift is in the direction of the *prevailing* wind. This statement does not appear to represent the condition of affairs accurately. The prevailing winds generally throughout this country are from the south-west, blowing from that direction for about two-thirds of the year. The direction of the movement of the drift varies on different parts of the coast. Generally, and subject only to exceptions due to local causes, the direction of the drift along the western side of England is northwards; along the south coast it is easterly, and on the east coast southerly. In each of these cases the movement of the drift is in the same direction as the main set of the flood tide.

To take another example from the south-east corner of England, the area of which is so limited that any wind which prevails on one part of the coast must also prevail on the rest. On the south part of the coast the direction of the littoral drift is eastwards; on the east, from Dover to the North Foreland, it is northerly; and up the southern side of the estuary of the Thames the movement of the shingle is westerly; while on the north side it is south-westerly. In all these cases the drift travels in the same direction as the flood current. To take a still more limited area, that of Lyme Bay, where local causes modify the set of the tides and the travel of the drift. This example is especially to the point. The movement of the shingle along the Chesil Bank, which is situated in this bay, has formed the subject of two papers and discussions at the Institution of Civil Engineers, and also has been dealt with by geologists and the committee of the British Association on Coast Erosion. It was on observations made at the Chesil Bank that Sir John Coode deduced the law as to the travel of shingle, which has since generally, although not without question, been accepted as correct.

Lyme Bay is situated on the south coast of England, between Start Point and Portland Bill, the distance between these projec-

tions being 48 miles, the depth of the bay back from a line drawn between these points being 25 miles. At the eastern end is situated one of the largest banks of shingle in this country, known as the Chesil Bank. It is 15 miles long, and varies in width from about 500 to 600 feet, and in height from 20 to 40 feet. This bank was probably formed when the tides were higher than they now are, and when the rest of the coast-line and beach received the form which they now assume. Shingle, however, still continues to move along the foot of the bank. The tidal flood current in the offing of the bay sets easterly; in the bay it runs round Start Point, and generally follows the same direction as the coast-line for about two-thirds of the distance. The offing tide, striking the projection of Portland Bill, causes a great disturbance of the water and a set into the bay, which, meeting the tide coming from the other direction, eddies round out of the bay in a southerly direction, as shown by the arrows in the illustration, Fig. 23.

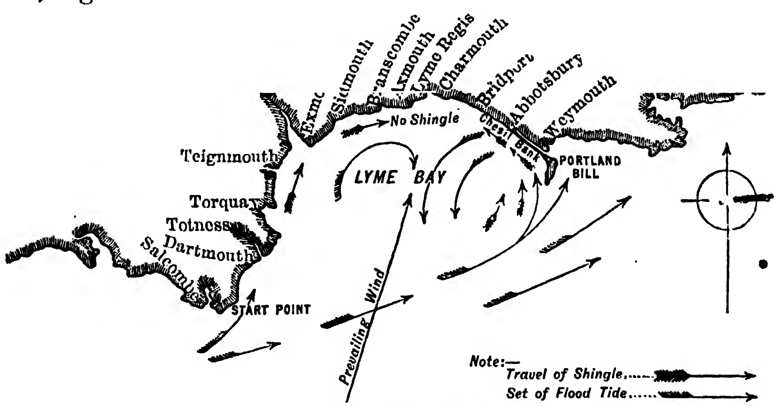


FIG. 23.—Plan of Lyme Bay.

The prevailing wind, and also the winds that cause the highest tides and largest on-shore waves, are those from the south-south-west, and setting north-north-east. The direction of the Chesil Bank is from north-west to south-east. The material of which the beach of the bay is principally composed is shingle; this comes from the erosion of the cliffs at the western end of the bay. This shingle travels along the shore, first following the coast-line in a northerly direction, and then eastward as far as about Axmouth, where the shingle becomes very scarce, and in places is entirely absent. Some miles beyond this the Chesil

bank commences. It does not appear that this bank materially increases or decreases in size, but there is a movement of the shingle along it generally northward and westerly, or in the opposite direction to that of the material at the other end of the bay. The movement of the shingle along the Chesil Bank, and in the bay generally, is not in the direction of the prevailing wind, but varies in different places, and follows more nearly the set of the flood current. There is not, however, a regular continuous set in any one direction. In some parts of the bay, with the wind from south-south-west and with heavy ground swells, the beach becomes denuded; in others, as at Sidmouth, the shingle is accumulated with these winds, the shingle here travelling east or west, according to the direction of the wind. Near Axmouth, the shingle accumulates in fine, calm weather, but is carried away with southerly winds. At the east end of the Chesil Bank the largest pebbles are found, and these are transported on to the beach by the current, which sets in this direction. At this part of the bay the sea is the roughest, and there is most disturbance of the beach, large ridges, at considerable depth below low water, advancing towards the shore, and retreating as gales from different quarters prevail.

The travelling shingle along this coast has formed bars across all the rivers which empty into the bay. The Chesil Bank has completely blocked the exit of several small streams, which collect in a wide channel at the back, which runs parallel with the bank for about ten miles, and discharges into the sea at the eastern end. The river Otter, near Budleigh Salterton, at the west side of the bay, which is about 60 feet wide, is barred by an accumulation of shingle; and the Sid, near Sidmouth, about the centre of bay, is completely choked by the shingle, through which the water percolates to the sea.

The banks of shingle which are to be found up estuaries all either lie in the line of the flood current or move in the same direction, and in many places are in sheltered situations where the prevailing winds cannot be the cause of their movement or accumulation. Examples of such beds of shingle may be found in the estuary of the Thames, between the Isle of Sheppey and Sheerness, the pebbles being moved westward by the tidal current towards Sheerness. At the upper end of the estuary of the Wash, at Snettisham, there is a large accumulation of shingle, the pebbles being brought there by the tidal current from the

flints of the chalk cliffs on the north of the Norfolk coast. There is also a large bank of shingle in the estuary of the Ribble, between Lytham and St. Anne's; also in the estuary of the Seine at Villerville, where it is sheltered from the gales, but travels with the flood current.

Gales alone cannot be the cause of the existence or maintenance of bars. These are only occasional, and their continuance is not long enough to cause a continuous transport of material. If the supply of material depended solely on causes operating in stormy weather, the bar would diminish in summer, when frequently there is a long continuance of calm weather, and increase when gales are most prevalent. In the longest calm bars do not disappear, and when the shore extends out beyond the line of the bar, it may remain unaltered even in stormy weather. As already shown, alterations may take place due to gales, and the bar be increased or partly removed, but after a time it returns to its normal condition.

It is, however, an undisputed fact that during gales large quantities of material are disturbed and transported to fresh places. An instance of the mighty power of the waves in heaping up and dispersing material was quoted by Sir John Coode in the discussion on the paper on bars already referred to, when a quantity of shingle, estimated at 63,000 tons, was moved along the Chesil Bank in one night, and at the next spring tide 45,000 tons were thrown back on the beach again; and that in a month afterwards 76,000 were removed by the sea. Another case, which occurred in Madras harbour, was given by Mr. Thorowgood. The swell of the sea, owing to an alteration in the direction of the shore currents by the extension of the rubble mound put in for the foundation pier, in one single night completely buried the mound, which was in from 3 to 4 fathoms of water, 3 feet deep with sand; and on further examination it was found that frequently on that coast there was a movement of the sand by wave action from the 4½-fathom line inwards, the mass of sand thus capriciously moved at one time being estimated at 2000 tons.

Mr. Kinahan, in a paper contributed to the *Proceedings of the Institution of Civil Engineers* in 1879 (vol. lviii.), on "The Travelling of Sea Beaches on the South and East Coasts of Ireland," states as the result of twenty years' observation, that the ordinary wind waves assist the flood tide when they are

moving in the same direction; when they strike the beach at a right angle, or nearly so, they pile up the shingle; if coming in a more or less opposite direction, they cut out the beach; ground swells breaking on the coast-line perpendicularly generate a back wash that cuts out the beach. The flood tide runs eastward on the south coast, and northward on the east coast. The flood tide generates three classes of on-shore currents, due to headlands and bays. All these currents carry material along the beach with them. With regard to the size of the material moved, he found stranded on the coast of Galway, after a storm, large blocks of stone weighing from 2 to 3 cwt., which had travelled through water more than 15 fathoms deep. As the tide rose these blocks drifted towards the land, and in twenty-four hours nearly the whole of these blocks were collected in horizontal lines. He also noticed that the movement of large stones in deep water was greatly assisted by the floating property of the seaweed attached to them.

In the opinion that the tidal currents are the most effective agents in carrying material along sea beaches in Ireland Mr. Kinahan was supported by Mr. L. Estrange Duffin, in a paper read before the Royal Irish Academy in 1879, in which he stated that his experience along the coast of Waterford satisfied him that although the winds often assist the tides and hasten the travel of the shingle, yet the tidal current was the active agent in its transport.

The opinion here expressed, and the facts quoted, accord with those which have been arrived at by engineers in America. Professor Haupt, in a paper on "Littoral Drift," contributed to the American Society of Engineers, said that a careful examination of the coasts of New Jersey satisfied him that the flood tide and littoral currents were more effective in moving drift than the prevailing winds, and in this he was supported by facts brought forward by other members of the society.

Conclusion.—The conclusions to be drawn from the facts given in this chapter may be thus summarized.

That the causes which operate in maintaining the existence of bars in tidal estuaries are due to the sea, and not to the inland waters.

That their existence depends on a struggle between the waves and the littoral currents engaged in depositing material

across the mouth of the outfall channel, and of the ebb current in removing the same.

That in designing works for the removal of bars and the prevention of their re-formation, the object sought should be to strengthen the ebb current, so that it may prevail over the flood; to push out the line of travel of material along the shore so far that it crosses the outfall in deep water, and where the strength of the littoral current is sufficient to prevent its being carried into the channel by the flood tide; to increase the depth of water at the outfall so as to neutralize the action of on-shore gales and breaking waves; that piers carried out for directing the current should be so placed as to produce the greatest effect from the tidal scour.

The laws to be observed for developing the propagation of the tidal wave, and the form to be given to the channel for increasing to the fullest extent the scouring action of the currents, are dealt with in the chapters on "Principles of Improvement and Training."

That the movement of littoral drift is in the direction of the current of the flood tide, and that this action is aided by those on-shore gales which have the effect of raising the highest tides.

"Bars at the Mouths of Tidal Rivers," W. H. Wheeler, *Min. Proc. I.C.E.*, vol. c.; "Tidal Rivers," by Capt. Calver, 1853; "The Improvement of Tidal Rivers," W. A. Brookes, 1841; "River Engineering," D. Stevenson, 1872; "River Bars," J. T. Mann, London, 1881; "The Motion of Shingle Beaches," H. R. Palmer, *Phil. Trans. Royal Society*, 1834; "Description of the Chesil Bank," J. Coode, *Proc. I.C.E.*, vol. xii., 1853; "The Origin of the Chesil Bank," J. Prestwitch, *Proc. Inst. C.E.*, vol. xi., 1875; "Groynes and Coast Erosion," Pickwell, *Proc. I.C.E.*, vol. li.; "The Travelling of Sea Beaches on the South and East Coasts of Ireland," Kinahan, *Proc. I.C.E.*, vol. lviii., 1879; "Report of Committee of British Association on Coast Erosion," 1884; "Littoral Movement of the New Jersey Coast," L. M. Haupt, *Trans. American Society C.E.*, vol. xxiii., 1890.

CHAPTER VIII.

PRINCIPLES TO BE OBSERVED IN IMPROVING TIDAL RIVERS.

THE physical characteristics of every tidal river vary. It is, therefore, impossible to lay down a complete code of rules which shall strictly apply to all rivers, or to expect that works which have been successful in one river may be applied without modification to another with equal success. There are, however, certain principles and results gained by experience which apply to all rivers. It is essential that a knowledge of these shall be acquired before any attempt is made to interfere with tidal channels. Having first acquired a complete knowledge of the tidal and other conditions of the river to be improved, an intelligent application of those principles of action acknowledged to be correct will afford the surest guarantee of success.

Of the subjects on which there is a diversity of opinion, an engineer must form his own judgment from a study of the facts and results obtained from works already carried out.

The best means of improving the outfall of a tidal river through an estuary is a subject on which no attempt should ever be made to dogmatize. Schemes, however well considered, should only be regarded as tentative, and the results carefully noted as the work goes on, and such modifications made as the results obtained dictate.

Principles to be Observed in Improving Rivers.—The primary object to be obtained in dealing with a tidal river is to improve its facilities for navigation. This can be accomplished by removing shoals and obstructions, and thereby increasing the depth of the water; by easing sharp bends and regulating the width of the channel; and by increasing the duration of the time during which the river can be used for navigation.

The main principles to be observed in designing works for effecting these objects are—

1. That the conditions under which the river exists should be maintained as far as practicable, the natural forces in operation being controlled and directed to the best advantage.

2. That all schemes for improving or altering channels should be designed in accordance with the laws of nature as defined by science.

3. That the river and its estuary should be considered in its entirety, and that no works for local improvement should be undertaken without due consideration being given to their effect on other parts of the system.

4. That the aim should be directed to obtaining a general balance of all the forces in operation, so as not to give an undue preponderance to any one; and to establish such a state of stable equilibrium as will conduce to a permanence of the results obtained.

5. That, while the low-water channel should be maintained at a width sufficient for the discharge of the land water in floods, it should not be too wide to prevent the greatest effect being obtained from the scour; that there should be ample width for the navigation and for the lateral extension of the tidal flow; and that the estuary should be conserved as a receptacle for the tidal water, so far as such water acts as a feeder to and assists in maintaining the main navigable channel.

6. That the tidal wave should be propagated to the furthest limit practicable in one deep uniform channel, in which the tidal water is made to concentrate its energy to the fullest extent.

7. That there should be a free entrance for the tidal wave from the sea; and that the waterway should uniformly diminish in width from the mouth; and that the direction of the channel should assume the form from which the best results can be obtained.

8. That when the natural conditions of a river do not afford sufficient depth for its navigation, or when the channel is obstructed by bends and contractions of varying widths, it should be deepened by mechanical means, and regulated by training and the removal of abrupt bends.

The Commission of Engineers appointed by the Dutch Government to report on the various schemes which had been proposed for the improvement of the river Maas, laid down, as a preliminary to their report, the following principles as applying to tidal rivers:—

1. That theory and experience have taught, and the evidence brought before the commission confirms, that the most influential agent in maintaining the depth of navigable channels is to be found in the velocity with which the water moves through the channel. When the velocity and volume of water are insufficient to maintain a section adequate to the needs of commerce, the end can only be attained by dredging.

2. The incessant action of the tides and waves maintains in constant motion the sands along the coast, establishing a slope on the coast of Holland of from 250 to 140 to 1.

3. The drainage water which flows out of the river on the part of the coast under consideration is inadequate to maintain a channel through this slope of the shore. It is, therefore, to the action of the tides that the maintenance of depths at the mouths of the rivers is to be attributed.

4. The total effect depends upon the velocity and volume; both increase with the tide range, that is, with the difference between high and low water. Where the tide range is very small, as in the Zuyder Zee, the Mediterranean and other seas, it is found that the drainage waters alone are inadequate to maintain a navigable depth of channel.

5. The tidal range cannot be increased, but the direction and form of entrance into the sea may be regulated, and the breadth limited in due proportion to the volume, and thus the depth may be increased.

6. That the outlets of the rivers on this part of the coast into the North Sea have all a curve to the southward (the direction from which the flood tide comes), whereby they better intercept the tidal current flowing across the channel.

7. Rivers do not discharge the same volume through every section, but the nearer the sea the greater the volume. Hence to maintain an equal depth the width must be greatest at the outlet, diminishing funnel-wise in ascending.

8. The further up the channel the tide can be enticed, the more powerful will be the downward flow of the ebb.

The following is an abstract of the views which were adopted in the section on tidal rivers at the International Congress on Inland Navigation held at Paris in 1891 :—

1. That, the size and depth of a tidal river being mainly due to the tidal flow, any works which increase its volume and extend its influence, such as the removal of obstructions, dredging

hard shoals, and the lowering of the low-water line by deepening the channel, effect an improvement in the river for navigation; whilst any works which restrict the tidal influx, even though producing a local deepening by scour, are liable, unless under exceptional conditions, to injure the general navigable capabilities of a tidal river.

2. The regulation of the banks of tidal rivers, so as to remove abrupt variations in width, equalizes the tidal flow, reduces accretion, and facilitates the tidal influx, and therefore constitutes an important means of improvement, even if accompanied by a slight reduction of tidal capacity at certain parts by the obliteration of indents, which is generally more than compensated for by the improved scour, and consequent lowering of the low-water line, especially if accompanied by the removal of shoals.

3. The extent of the filling basin necessary for the maintenance of rivers and of their mouths depends more on the methodical and rational laying out of the sections and widths rather than on the lateral reservoirs, which sometimes present grave inconveniences, and which ought only to be constructed in special cases.

4. Dredging furnishes a most valuable method of deepening a tidal river, which may be carried far beyond the limits of natural scour if the trade of a river port justifies a large expenditure; and a small river may be thus converted into a waterway accessible by large vessels at all states of the tide, of which the Clyde forms a notable instance. Furthermore, by means of this dredging, the facilitating of the transmission of tides and the increase in the flood and ebb are effected, to the improvement of the mouth. By means of the improvements which dredging has received in recent years, the scope of this kind of improvement has become greatly enlarged.

Captain Calver, in his treatise on tidal rivers, lays down the following laws as applying to works carried out for the conservation or improvement of tidal channels:—

1. That the navigable condition of the outlet of a tidal river can only be maintained by tidal water, and that its extent as to sectional capacity will be proportioned to the amount admitted.

2. That a fresh-water stream is powerless to maintain a sea outlet and to keep down a bar.

3. That every portion of the tidal expanse has a value peculiar to itself, inasmuch as it is continually operative. That

any reduction of the tidal capacity is wholly against experience, and is opposed to true theory and successful practice.

4. That the supply of material which encumbers the outfall of tidal rivers is from the interior, and not from the sea; and that the strength of the ebb to discharge it is greater than that of the flood to return it.

5. That the system of improving a river by longitudinal training walls is the realization of the best possible navigable condition of a river without the sacrifice of tidal volume.

6. That dredging as a system is an error in principle, being an attack upon the effect rather than the cause; but is valuable as an adjunct to training in preventing the soil from being scoured from the shallower into the deeper portions of the navigation, and in breaking up the crust of the bed when it is sufficiently indurated to resist the improved energy of the current.

7. That straight reaches should be avoided, as the deep-water track in a straight reach, being liable to be acted on by slight causes, will be apt to range from side to side, and thus become a source of derangement to the permanency of the deep water.

8. That in carrying out improvements the high-water level is to be accepted as a nearly fixed point, not to be materially influenced by river works. That the depression of the low-water level is all important as ensuring an increase in the tidal duration, and of the tidal quantity, and of the navigable depth. That the improvement of the tidal propagation is a test of the improvement of the tidal compartment.

9. That all improvements should begin in the lower reaches of a river or estuary.

The principles to be observed in improving tidal rivers as here given present very little variation, and may be taken as fairly representing the opinions of the engineers of this country, in France, Holland, and Germany.

Preservation of Natural Conditions.—With regard to the first law laid down, that the existing character of a river should be maintained as far as possible, it will be found that in many cases a due regard to the circumstances under which a tidal river exists, with a view to improving and directing the tidal flow along the existing course, will conduce to better results at very considerably less cost, than by a disregard of these conditions and the cutting of new straight channels. The construction of such new cuts has frequently resulted in an alteration of the

tidal conditions in a manner never anticipated, and affecting the action of the tidal water in the lower reaches and on the bar, or the flow of the tidal wave to an extent that has detracted from the improvements otherwise effected.

In like manner local improvements, carried out without a due consideration of their effect, have led to results which have damaged other parts of the river. No one part of a tidal river can be modified without a reaction more or less strong on the other parts. As much as possible, improvements affecting different parts of a river should be carried out simultaneously, so that their effects may balance each other, and a new condition of stable equilibrium be established.

It is equally essential that the result of bringing into active operation any particular force should be well considered in its relation to other effects, so that a proper balance of forces be maintained. For example, the velocity may be so increased as to erode and deepen the bed of the channel, and be so great as to carry away the detritus; but this increased velocity may be the agent of its own destruction by unduly increasing the size of the channel. This excess of velocity may also prove of great inconvenience to the navigation. On the other hand, by checking or retarding the tidal flow, or by diverting the land water, the scour may become so weak that deposit will take place in the channel, or a bar be formed at the mouth of the river. A channel may be laid out, in the interests of the navigation, of a great width, but out of proportion to the fresh water ebb and the tidal rise and run, in which case it will be difficult to maintain the depth required.

The material of which the channel is composed must also be considered. Soils of a tenacious character will resist the impact of the water moving at a velocity that would erode those of a less tenacious consistency, and unless expensive works of protection are resorted to, the velocity must be proportioned to the tenacity of the soil. The amount of slope to be given to a bank is also regulated by the same considerations.

The bends and pools found in all natural rivers are simply the result of contending forces acting either horizontally or vertically. Where the course of a river remains stable, it shows that, by an enlargement of the sectional area at any given place, the velocity has become sufficiently checked to prevent erosion, or that the tenacity of the soil is equal to sustaining the

impact of the water and its force, and that thus the regimen of the river has become established.

So, in carrying out works for the improvement of channels in sandy estuaries, it will be found much less costly and more effective to direct and develop the one main low-water channel, than to attempt to make a straight channel in a new direction by training regardless of existing circumstances. However unstable channels in sandy estuaries may be, a careful examination of the circumstances will show that there is one course in which the deepest water is maintained, and in which the channel is most stable. By coaxing the whole of the ebb and flood into this channel, by blocking up subsidiary channels, and by assisting the scour by deepening the shoal places, and thus concentrating the full effect of the tidal current in one course, a good navigable channel may be obtained at a comparatively small cost; whereas by attempting to drive a channel through sands in a direction which nature has not selected will be found costly to carry out and difficult to maintain. The stability of channels in sandy estuaries, through which the force of the flood tide permanently acts in one course, and which are undisturbed by the action of land freshets, is evidenced by the so-termed "blind channels" which are to be found in nearly all large sandy estuaries. These low-water channels have their greatest width at the lower end, and gradually converge upwards, and often have a straighter course and deeper water than the main stream through which the upland water passes to sea. In some cases they are only separated from this stream by a shallow bar, but in others are blind channels terminating at their upper ends in the sandbeds which dry at low water. These channels also afford proof of the ability of the tidal water alone to maintain a channel when neither injured nor aided by the upland water. The erosive action of the flood tide is the sole agent of their maintenance.

Inland Waters.—Although the tidal water is the principal agent in maintaining rivers and adapting them for the purposes of navigation, yet the inland water coming down the river deserves consideration, and its discharge must be provided for. The water coming off the land is a valuable agent in scouring and maintaining the channel of the river above the influence of the tide, and in assisting in transporting out of the channel material which otherwise would remain and contract its area. Any

works in the tidal portion that restrict the fresh-water discharge will lead to land floods and serious damage and loss to property. The increase of the sectional area of a tidal river, the deepening of the bed and the lowering of the low-water line, although allowing the tide to extend further up the river, is a direct advantage in the prevention of floods. If the section of a non-tidal river be made sufficiently large to carry off the water in occasional heavy floods, the velocity of the water will be so weakened during the ordinary flow that it will not be able to carry away the detritus washed down the river, and the channel will become again shoaled, and continue to shoal until the original diminished section be again attained. Where, however, the enlarged section becomes filled daily with tidal water, the continual ebb and flow will prevent accretion. In floods this larger section will provide for the increased volume of fresh water, only excluding for the time a like amount of tidal water, and the channel will thus automatically adjust itself to the varying conditions of the river.

The drainage water coming down a river is sufficient, if aided by the tidal oscillation, to keep a well-trained river free and clear from deposit, however wide or deep. The quantity, however, is limited, and cannot be increased, and in dry weather recedes within very small limits. It is, therefore, undesirable to overload it, or to allow the channel to be encumbered with unnecessary material, whether due to shifting sands, the erosion of banks, or the detritus and other matter contained in sewage poured in from towns, or refuse from manufactories.

Mr. Brown, in a paper (*Proc. Inst. C.E.*, vol. lxvi.) on the "Relative Value of Tidal and Upland Water," contended that the scour and maintenance of rivers are due mainly, if not entirely, to the inland water, and that the silt which tends to choke up tidal channels is almost wholly due to the tidal, and not to the fresh water; and endeavoured to show that the tidal water brings up more silt on the flood than it takes out on the ebb. If this contention is limited to the transport of material out of a wide estuary into a narrow tidal channel, in which there is a restricted tidal run accompanied by a deficiency of inland water, the contention is no doubt to a certain extent correct, as shown by the facts recorded in the previous chapter. The river Avon, from which the observations were obtained on which the above theory was based, complies with these conditions. The tidal

range of this river has been partially stopped by a dam placed across the river at Netham, above Bristol, which tends to the deposit of the material in suspension in the tidal water, and which, in the absence of freshets, accumulates in the bed and on the sides of the channel. This is scoured out again when freshets occur. The inference that the author drew, that this material comes entirely from the sea, because the water in the Severn is clear at Worcester and muddy at the mouth of the Avon, cannot be substantiated, as the water in the lower part of the Bristol Channel is brighter and clearer than it is at Worcester.

There can be no dispute that the upland currents bring down with them a large amount of detritus; that this remains, in a river like the Avon, in a state of oscillation, or at certain periods a portion becomes deposited, to be again put in motion and carried down the river, and finally carried out to sea when the heavy freshets come.

Mr. Stevenson says that, so far as his experience goes, the detritus brought down by the fresh water is more to be feared in a tidal river than that carried by the sea.

In fact, it may be said that upland water contains in itself both an evil and a remedy; that the currents it creates, while acting as agents for transporting material into the channel, also operate in clearing it and maintaining its depth.

For the purpose of removing material out of a newly trained channel, too much reliance should not be placed on the scour to be derived from the tidal flow, however large the volume may be. The tidal flow is due to an oscillation, only the same quantity of water passing out of a river as flowed into it. Matter in suspension becomes diffused amongst this volume, and is then carried away out to sea. Sand and detritus too heavy to remain in suspension is rolled backwards and forwards by the oscillating current, gradually but slowly moving downwards and out to sea. When, however, the ebb tidal current is reinforced by inland water, especially in heavy freshets, the travel seawards becomes much more rapid, and the scouring and deepening of the channel more effective.

The inland water is therefore a valuable aid in the deepening and maintenance of newly trained tidal channels.

There is also a point in tidal rivers, at the meeting of the tidal and land water, where the energy of the flood tide ceases.

At this point, varying from time to time, there is a tendency for material rolled along the bottom by the flood tide to remain and cause a shoal. In some rivers, even if there is a free tidal run, but where the supply of inland water falls off very much in dry weather, shoals will accumulate to a sufficient height to impede the navigation of the higher reaches of the river. In this case the inland water due to rain is a valuable agent in removing such shoals and in preventing their becoming permanent.

The diversion of the inland water due to its drainage area from a tidal river, and sending it to sea by some other course, will invariably prove detrimental to the maintenance of the channel. River channels by natural causes have adapted themselves to the discharge of a certain volume of water, varying in quantity at times, but retaining normal conditions. By abstracting any material portion of this water the balance of forces is disturbed, and the *régime* of the river destroyed. Several instances could be quoted where the diversion of the water from its original channel to another has led to the shoaling of the outfall and of the channel.

In the river Somme, the upland water was diverted above Abbeville and discharged into a new cutting made for a canal. After this was done the sand accumulated in the river-bed, and to a great extent filled it up, so that lighters drawing 3 feet could hardly get up the river to the village of Grand Port, 5 miles above St. Valery.

The river Stour, on the south-east coast, so doubles round in its course that at one point there is only about a mile across the land, the distance by the water being eleven miles. The authorities interested in the drainage made a cut across this bend for the purpose of discharging the water in freshets. The consequence has been that the deposit accumulates much more rapidly than formerly, to the injury of the navigation up to Sandwich, and the channel has to be continually dredged out.

Propagation of the Tidal Wave.—One of the most important objects to be kept in view in designing works for the improvement of a tidal river is that the tidal wave shall be developed to the fullest extent.

Improvements which are beneficial to the navigation are also necessary for a free entrance and run of the tidal water.

The tidal wave can only be propagated to the fullest advantage in a deep channel.

The deepening of a tidal channel is not only of advantage to the navigation, in affording accommodation for vessels of larger burden and deeper draught, but it hastens and prolongs the time of tide, and allows the greatest advantage to be obtained from the tidal range. The removal of shoals and lowering the bed of a river also allows the tidal water a longer range, and provides a larger volume of ascending and descending water, which operates twice every day in scouring and maintaining the channel. It has been truly remarked by M. Mengin, in his memoirs on "Tidal Rivers," that health, like disease, engenders itself, and that the depth of a river may be regarded as its health.

The free propagation of the tidal wave depends much more on the depth and absence of obstruction to the flow than to width or sectional area.

The more vertical the sides of a channel are, the more favourable they are to the transit of the tidal wave. Mr. Scott-Russel, in the experiments made on wave action, found the velocity of a wave was considerably greater in a channel with vertical sides than in one in which they were shelving.

Mr. Stevenson, in his work on "River Engineering," has laid down the following axioms with regard to tidal propagation:

1. That decrease of the low-water slope of a river is followed by an acceleration of the rate of propagation of the tidal wave.

2. That the rate of propagation does not bear a constant relation to the amount of slope, although to some extent modified by it.

3. The rate of propagation is due to depth, influenced by the slope of the surface, form of channel, and obstructions.

4. One of the first results of training, dredging, and improving a tidal channel is a depression of the low-water line in the upper reaches, and of the surface inclination of the water throughout. This, while of great service to the land-draining by the river and in the prevention of floods, is also generally beneficial to the river, and particularly in the outfall and lower reaches, by increasing the quantity of tidal water which passes up and down the river. The amount of the depression of the low-water level in the upper reaches of a river, consequent on improvements, may be taken as a sure indication of benefit conferred.

5. The benefit derived from removal of shoals extending across the channel by dredging is greater than in proportion to the cubic contents of the material removed, as these shoals act as sunk weirs, holding up the low-water line; the quantity of additional tidal water is therefore that due to the wedge-shaped section of the depressed low-water line, in addition to the quantity due to the solid material taken out.

These axioms appear to the author to convey a sound definition of the results due to tidal propagation.

The distinction between the velocity of the tidal current and the rate at which the tidal wave is propagated in a river is dealt with in the chapter on the "Tides," and it is there shown that, while the current may only run at a velocity of two or three miles an hour, the tidal wave may be propagated at the rate of 20 or 30 miles an hour where the depth of water in the river is sufficient.

The velocity of propagation in the open sea is proportionate to the square root of the depth, but there are so many circumstances affecting the flow of the tide in the confined channel of a river that this rule cannot be taken as applying to rivers generally.

From the tables given in the chapter on "Tides," the inference may be drawn that approximately the rate of the foot of the tide in rivers varies as the depth, each foot of depth of water giving a rate of progress of the foot of the tide of one mile an hour. At the head of the tide, the rate of the propagation follows more nearly the law which governs the motion of the tidal wave in the ocean.

The effect of shallow water, although retarding the first flow of the tide, does not much affect the level of high water. In a river having a steep slope with shallow water, the total time of flow is diminished, and the total quantity of water flowing up and down is diminished. The wave-action under such circumstances is lost, and the tide, instead of being properly propagated, forces its current up the slope of the bed of the river. The momentum is thus rapidly absorbed, and in consequence the tidal run is shortened and its influence lost.

The appearance of bores in shallow rivers is an evidence of the disadvantage of the want of depth. In rivers in which bores occur, they become much modified or entirely disappear when the depth of water in the channel is increased by freshets. Under

the same circumstances, also, the velocity of the propagation of the tidal wave is increased. Thus, on the Severn, Admiral Beechey found that the advance of the tidal wave increased from 4 to 10 miles an hour when the river was under the influence of freshets.

In rivers of great depth, like the Mississippi or the Amazon, although the rise of the tide is small, yet its influence is felt for several hundreds of miles up the channel; whereas in shallow rivers having a very much larger rise of tide, the influence only extends for 10 or 20 miles.

Any obstruction that checks the free flow of the tide is detrimental to its propagation.

Weirs placed across tidal rivers deprive the lower reaches of the advantage to be derived from the full amount of tidal scour. The quantity of tidal water is still further diminished by the quantity of material which accumulates immediately below them in dry seasons. Instances of this have been given in the previous chapter.

In some rivers, as in the Dee and the Avon, these weirs are only partial obstructions, stopping the first flow of the tide, but allowing the last two or three feet to flow over and run up the river. The full oscillating action of the tide is, however, injured by such stoppage. The first wave, instead of moving freely forward, is checked by the weir and driven back, meeting the succeeding waves. The whole tidal *régime* is thus disturbed, eddies are created, and the sediment in suspension, which would remain in this condition if the water were kept flowing, is deposited, raising the bed of the river, and remaining until freshets come and remove it.

The amount of material which thus accumulates in the river takes the place of tidal water, and deprives the river of the scouring action, already seriously diminished by the quantity cut off by the weir.

The improvement of the channel, and with it the propagation of the tide, will frequently result in raising the level to which high water obtains up the river, thus gaining, by the elevation of the tide, provision for deeper-draft vessels, which could only otherwise be obtained by excavating the bottom at considerable cost.

The facts given in the previous chapter show that extensive improvement may result in thus raising the level above that

which formerly existed, even when this level was as high as that of the tidal wave in the sea or estuary; but that small improvements, while having a considerable effect on the low-water line, do not affect that of high water. Also, further, that when the high-water line at any particular port is above that of the tide in the open estuary, this may be reduced by altering the shape of the channel and the conditions of tidal flow.

At Shoreham, the widening and deepening of the harbour mouth resulted in depressing the rise of spring tides from 18 feet to 16 feet. At Newhaven, also, the works carried out for improving the entrance to the harbour, although causing the tide to be 40 minutes earlier, have made the rise 2 feet less than formerly.

In the Tyne, on the other hand, the deepening of the channel has resulted in making the high-water level 12 inches higher at Newcastle, and in the Clyde 10 inches higher at Glasgow.

Width and Direction of Channels.—The circumstances to be taken into consideration in determining the width of a channel are: 1. The requirements of the navigation. 2. The volume of tidal water to be provided for, influenced by the length of the tidal run and range of the tide, and ensuring its free flow. 3. The discharge of the fresh water under ordinary conditions and in floods, and obtaining the greatest advantage from it as a scouring agent.

As regards the requirements of the navigation, this will depend on the amount of traffic frequenting the port. Where this is small, a minimum low-water width of 100 to 120 feet will be sufficient for two vessels to pass. In fact, a very large amount of business may be conducted over a river having even a less width than this, as, for example, in the Avon leading up to Bristol docks, where the width of the river at the dock entrance is only 50 feet at the bottom. In the Witham the channel immediately below the dock is only 75 feet at the bottom and 100 feet at the low-water line, the width gradually increasing downwards. No difficulty is found in navigating vessels of from 1500 to 2000 tons register up and down this river. It is obvious, however, that a greater width than this is desirable where it can be procured. As some guide, it may be mentioned, that the width of the Suez Canal is 72 feet at the bottom; of the Amsterdam Canal, 89 feet; and of the Manchester Ship Canal, 120 feet.

In the propagation of the tide, it is essential that the channel in the lower reaches shall not only be wide enough to allow of a

free admission of the tidal water, but shall be so regulated as to allow the tidal water to have a free and unimpeded run to the furthest limits attainable, and that for this purpose the channel shall uniformly widen out from the lower end. Where the tidal run is short—as, for example, where it is stopped by a dam across the river, as in the instances already given—the run of the tidal wave will be shorter, and a less quantity of water will require to enter and pass up the river than where the tide has a long uninterrupted flow. A channel with a short tidal run may therefore have less width. If the channel be made too wide, and be not uniformly contracted, the scouring action of the ebb will not be developed to the fullest extent. If, on the other hand, it be too contracted, the tidal flow is throttled, and cannot reach so far up the river. It will also have to make up for want of area by increase of velocity, and a bore will be created, as in the case of the Seine. This excessive velocity is dangerous to the navigation and destructive to the banks.

The discharge of the fresh water varies considerably in volume, shrinking into very narrow dimensions in long-continued dry weather, and increasing to a stream of considerable proportion in floods. The proportion of fresh water to tidal is, however, as a rule, so small that generally where the channel is of sufficient capacity for the tidal flow it will be sufficient to discharge the land waters. There are, however, instances of tidal rivers so contracted that in heavy freshets the velocity becomes so great as to interfere with the navigation.

In order to take full advantage of the scouring action of the water where the river is enclosed within banks rising above the level of high water, it is of advantage to have what are termed by the French engineers a major and a minor bed, the latter being only of sufficient width and capacity to retain within itself all the discharge at low water and during the last three hours of the ebb, the high-water banks being set back, leaving a cess or margin. The cess or space between the low-water channel and the bank should not be flat, as in this case the lateral expansion of the inflowing tide is sudden, and causes an eddying of the water detrimental to its free flow, but should join the bank with a gradual slope. The height of the banks of the low-water channel should not rise higher than half-tide level.

It is not possible to lay down any exact formula for regulating the widths of tidal channels. The circumstances attend-

ing every different river are so varying and complex that the determination of this matter must be settled by judgment and experience, strengthened by a consideration of the natural conditions in which a channel exists before improvement is commenced. In natural tidal channels it will be found that the width does not increase gradually, but the proportion of increase augments rapidly downwards the nearer the sea is approached. This law of increase may be expressed by the following formula, by means of which, the width at the upper and lower end of a river being given, the intermediate width at any given point may be found.

Let M be the mean low-water width of a tidal river at any place near the outfall; M′, the width at any other place some distance up the river; N, the number of miles between M and M′; x, any intermediate width required, distant N′ miles from M′; then—

$$x = M'(1 + C)N'$$

and C is determined by the formula—

$$C = N\sqrt{\frac{M}{M'}} - 1$$

The working out of this formula running into a great number of figures, it can only be conveniently used by the aid of logarithms. Applying this formula to the river Humber between Goole and Spurn Point. The mean low-water width at the former place is 924 feet, and at the latter 18,000 feet, and the distance 45 miles. The first column gives the mean existing widths at different points along the river; the second, the width as calculated by the above formula; and the third, the width supposing the channel augmented by an average mileage rate of increase.

River Humber.

Distance from Goole.	Mean low-water width.	Width by formula.	Width calculated by average rate of increase.
miles.	feet.	feet.	feet.
0	924	924	924
5	1,320	1,281	2,821
20	3,300	3,441	8,514
25	4,950	4,687	10,411
30	7,392	6,505	12,309
40	10,800	12,935	16,100
45	18,000	18,000	18,000

Applying the same formula to the Thames and the Trent, the results work out with a very near approximation to the actual low-water widths of those rivers.

Straight and Curved Channels.—For the purposes of navigation, and also for the free propagation of the tidal wave, a straight channel has advantages over a curved one, especially if the bends are abrupt and frequent. Straight reaches are not, however, found in practice to preserve the same uniformity of depth as curved channels under the varying conditions of flow to which they are subject. In all channels there is a tendency to deposit at certain seasons. Where the channel has been fixed in a straight reach, this deposit is not spread uniformly over the bottom, but gathers in shoals, first on one side and then on the other. Where, also, the bottom consists of sand or other material liable to erosion, the same effect takes place; the bed becomes scoured out in one part, and shoaled in another. These shoals, if spread out evenly, would not diminish the navigable depth to the same extent as they do in the tortuous course which they assume.

The particles of water in a stream move along with a rolling or circular motion; a curved channel lends itself more readily to this action than one that is straight. The natural condition of all rivers is to flow in a series of bends, and the same agency which effects this winding course operates in the bed of a wide, straight reach.

In a curved channel the greater velocity and scouring action of the stream is concentrated on one side, preventing deposit altogether, or causing it to accumulate on the convex side only, leaving the greater part of the bed of the river at its full navigable depth.

A concave bank sets up a scouring action in the current by diverting the particles of the water from their straight course, causing that rotary motion and boring action which occurs in all bends, and which operates in deepening the channel along the concave side.

From the observations made by Mr. Ripley, already quoted in Chapter III., it was found that in a natural river the water was ·58 per cent. deeper in the curved portion of the channel than in the straight reaches.

Mr. Stevenson says that this question, whether a channel should be curved or straight, cannot be determined by abstract

considerations, but by the relative positions of the points between which the stream is to be conducted. As a purely abstract question, he, however, was of opinion that it might safely be affirmed that a stream is most likely to follow a permanent course when directed by a concave bank; that the centrifugal force in curved channels has a tendency to draw the greater portion of the water to the concave side, and that the greatest scouring power will be found on that side; whereas in a channel directed by straight walls, the current, having no such bias for either side, is more easily thrown across from side to side.

Mr. Scott-Russel, in pointing out the evils which had arisen from the abrupt interpolation of portions of straight cuts into gently winding rivers, expressed the opinion that to make part of a natural river straight was a dangerous undertaking; that where the curves were gentle the natural bends should not be interfered with; that a river has an oscillating motion, and there is a similar process going on in it to that which goes on in a pendulous body. A pendulum set in motion continues to oscillate isochronously without the expenditure of any new force, and in like manner, if once a curve or bend was established in a river with considerable current, the mere fact of the commencement of curvature would give it a tendency to continue that curvature, and the stream would go on oscillating regularly to the sea in curves of opposite curvature. Continuity of a system of oscillation should therefore be maintained.

Captain Calver, speaking of the improvement of rivers, says that straight reaches are strictly to be avoided, more particularly where there is an established business upon the banks of the river to be trained. With a straight reach the deep-water track is acted upon by the most trifling causes, ranging from side to side at will, and it follows that under these circumstances there is no security whatever for the permanency of the deep water, either in a fixed channel or at the shipping berths.

The commission of engineers employed by the French Government to report as to the improvement of the navigation of the estuary of the Seine, in recommending the extension of the training walls through the estuary down to Honfleur, advised that these should assume a sinuous form, having a concave bend leading to the entrance to Honfleur harbour, in order that deep water should be maintained at the entrance jetties.

M. Fontaine, in designing works for the rectification of the

Rhine, avoided straight cuts and adopted curves. In the determination of the radii of curvature, he was guided by the inclination and force of the current. The maximum length of radius of curvature adopted was 5000 feet where the depth was 50 feet, and where the depth was 36 feet the radius was fixed at 4100 feet. General Eads also adopted a curved form for the jetties for the south pass of the mouth of the Mississippi. In the Weser no attempt has been made to straighten the channel, the existing curves being eased and improved. By cutting off abrupt bends, contracting the width where too great, fixing the course through sands, and deepening where required, a channel may be brought into a uniform condition with a series of gentle curves and rendered serviceable for navigation at far less cost and with better results than by making an entirely new cut. The course may not be so direct in the former as in the latter case, but the want of directness will probably be fully balanced by the more permanent maintenance of a uniform depth throughout, and the greater scouring power of the ebb and flood water.

In determining the direction of a curved channel, the radius of curvature should be as large as circumstances will admit, having regard to the due maintenance of the scouring action; and all curves should be tangential to each other or to the straight parts of the reach with which they are connected.

Where curves succeed one another there is always a tendency to shoal at the place of contrary flexure.

To obviate this, the width of the channel may with advantage be diminished from the summit of the bend to the point of reverse curvature. The amount of this reduction has been placed at from 5 to 25 per cent.

The Seine engineers have advised that the width of the training walls, when extended below Berville, should be reduced from 2950 to 2790 feet, and below this, at the next curve, from 4430 to 4265 feet, equal to a reduction of from 4 to 5 per cent.

With a curve of sharp radius there is not only the physical difficulty of steering a long vessel round, but the velocity of the current is also unduly increased, which adds to the difficulty of navigation.

A curve that may be navigable where the current is slack may be impracticable if the tide is running with much velocity. The radius of the curve should therefore bear a relation to the velocity of the current.

Mr. Mengin, in his "Memoir on the Tidal Seine," gives as a rule that the radius of curves ought to increase with the velocity nearly as the quantity AV^2, where A represents the width of the bed at low water and V the velocity, of the current in feet per second. So that if a curve of 1000 feet was sufficient in a channel 120 feet wide where the velocity was 3 feet per second, if this were increased to 4 feet the radius would require to be nearly double.

The least radius that a vessel 300 feet long can safely navigate in a channel having a low-water width of from 100 to 120 feet is 1000 feet, when the current is slack. Such a sharp curve is, however, undesirable. In the previous chapter several examples have been given of curvatures, and the class of navigation to which they are adapted.

There is no practical difficulty in lighting a curved channel or in so disposing the leading lights that a vessel may navigate it safely in the dark tides.

M. Fargue, Inspector-General des Ponts et Chausées in France, has paid considerable attention to the subject of curved channels, and has deduced a code of laws relating to the same from facts obtained from a series of observations on the Garonne, and also from an artificial channel constructed for the purpose of an inquiry by a commission appointed to report as to the best means of improving the access to the harbour of Bordeaux in 1876. This artificial channel was made with five curves, and was 200 feet long, 3·23 feet wide, and the same depth, these dimensions representing approximately a portion of the Garonne to a scale of $\frac{1}{100}$. The channel was supplied with a stream of running water from the canal, the bottom being formed on a bed of sand. The object of the experiment with this artificial channel was to ascertain how far the laws laid down by M. Fargue as to curves conformed to the actual facts as shown in the Garonne. One part of the channel was formed with curves laid out in accordance with his rules, and the other by a series of reverse curves and straight lines uniting with one another tangentially, a uniform width of 3·23 feet being maintained throughout. The summits of these curves were 40 feet apart, and the radius of curvature 32·80 feet. With these curves it was found that shoals were formed on the convex side of the channel, and deep water on the concave side; but the distribution was very irregular, and at each change of bend a bar ran

across the channel. The other set of reverse curves had a radius of 13·12 feet, the distance between the summit of the curves was 40 feet, the distance from the end of each arc 9·84 feet, making the straight line between the two 19·68 feet. The width of the channel at the summit of the inflexion was 6·56 feet, gradually diminishing to 4·92 feet, or 25 per cent. less at the point where the channel began to change from the concave to the convex bend, and then increasing again to the same width at the summit of the following curve. In the channels thus set out, the deep water maintained a regular and continuous curve round the concave side of the channel, across the centre of the intervening point of contrary flexure to the succeeding concave portion of the next bend.

From the observations obtained in the Garonne and in this artificial channel, M. Fargue has formulated the following rules:—

1. The longitudinal section of a river follows the form of the channel, there always existing a relation between the windings and the depth.

2. A channel presents more approach to regularity in depth when the curves vary in a regular and continuous manner.

3. In order that a channel may be stable, it must have a succession of curves alternately concave and convex, and uniting straight lines formed by the prolonged direction of the portion of the channel where the curve changes its direction. The distances between two consecutive points of inflexion must not be too small or too great. Where this is the case the bed consists of a series of pools and shoals. If the latter are dredged out they will form again.

4. In order that the deep water may be continuous and regular, the curves must have graduated bends, the channel being widest at the summit of the curve, and most contracted in the portion where the curve changes direction.

5. The width of the channel must vary with the amount of curvature and the distance the curves are apart.

6. The points of inflexion must be distant from each other by a distance depending on the width of the channel.

In the Garonne it was found that the deep water was continuous and the channel stable when the distances between the curves were not greater than 5000 feet or less than 3000; when the width at the summit of the curves was 656 feet, and

at the commencement 492 feet, or 25 per cent. less, and the distance between the points where the inflexion changed was 984 feet, or twice the least width of the bed.

Where shoals of shingle and sand have been dredged out of the river Garonne, and a direction given to the deepened part in accordance with these rules, the channel has subsequently maintained its depth and stability.

The Sea Approach.—The direction in which a channel enters the sea is a matter that requires very careful consideration, and can only be determined after a full examination of all the local agencies in operation. The impossibility of laying down any uniform direction as that which will give the best results, is shown by the fact that both natural channels and those which have been trained to the sea by artificial piers with satisfactory results effect their junction in diametrically opposite directions, some trending with the set of the ebb and flood current, some at right angles to the line of shore, and others trending away to the leeward at various angles. The advantages of the different directions, and the best method of directing a river channel into the sea, will be found dealt with in the chapter on "Training."

Methods of Improvement.—There are two methods of improving the channels of tidal rivers—training and dredging. Frequently the two are combined. Training is required for directing and controlling a channel, and bringing it within uniform bounds. The increased scour derived from the concentration of the energy of the water frequently results in the deepening of the channel. This is especially the case in rivers having a small tidal rise, and discharging a large amount of upland water.

In the Seine, nearly the whole of the material, amounting to over 80 million cubic yards, removed from the improved channel was carried out by the transporting power of the water, dredging in this case only being resorted to for the removal of hard clay shoals. In the Mississippi the bulk of the material was removed by scour, a small amount of dredging only being employed to hasten the work.

In tidal rivers training alone has not always been carried out with the same success. In the Tees, although the material to be removed was principally sand, the training works had to be supplemented by a very large amount of dredging before the required depth could be obtained. In the Maas, it was anticipated that by confining and directing the current the scour

would be sufficient to deepen and enlarge the channel to the required dimensions, and a very large amount of material was thus removed, but finally dredging had to be resorted to to complete the work and give the required depth. The training works in the Clyde have been of immense advantage in straightening the channel and regulating the current, but the depth which enables vessels of large capacity to reach Glasgow is due to the dredging operations. In the Weser the river was straightened by training, but the deepening was principally effected by dredging, the material removed being placed at the back of the training walls.

The effect derived from training takes time to develop, and the full benefit of the deepening is seldom felt until a considerable period after the work is completed. The benefit to navigation is more quickly realized when the deepening is also assisted by dredging, not only by the actual material removed by the dredger, but the disturbance of the material by the buckets assists its transport by the water.

When the bed of the channel is clay or hard soil, dredging of some kind becomes a necessity.

The great improvements which, during the last few years, have been made in dredging-machinery, particularly by the use of suction and hopper dredgers, have placed at the disposal of the engineer a means of deepening rivers at a much lower cost than formerly existed.

In many cases training, followed by subsequent dredging, has been carried out where the desired improvement could have been effected by dredging alone.

Tidal currents will, without any aid from training, keep to the same channel if sufficiently deep. The tendency of all flowing water is to run along the line of the deepest channel, especially if that line is in the direction most favourable for the run of the flood and ebb. The chief factor in the disturbance of the direction of tidal channels is wind, or the flowing down of occasional heavy freshets from the uplands. In a channel having a sufficient depth, the upland water bears a less proportion to the ordinary low water in the channel than when this is shallow; its power to divert it to a new direction is therefore less, and consequently it assimilates its action and direction to that of the existing low-water tidal current. The effect of wind in an estuary on the low-water channels is super-

ficial, and extends only a short distance below the surface. Gales which may be able to change the direction of shallow channels are powerless to do so in deeper water.

It is, therefore, quite possible, with such appliances as now are at the disposal of an engineer, to make a deep-water channel through an estuary composed of sand or free soil, which will afterwards maintain itself without the aid of training walls. An example of this will be found in the channel leading up to New York Harbour.

The lower bay, covering an area of two square miles, is open to the Atlantic Ocean, and has a tidal rise of 5½ feet. The Main Ship Channel and Gedney Channel lead from the harbour through this bay to the Atlantic (see Fig. 24). These channels were obstructed by four long shoals, over which the greater part of the vessels frequenting the port could only pass at high water. It was proposed by Major Gillespie to deepen these shoals 6½ feet by dredging, so as to give a minimum depth of 30 feet at low water. This scheme being referred to the Government Board of Engineers, they reported that they had little expectation that anything more than temporary relief could be obtained by dredging in a channel exposed to the full force of the Atlantic, and therefore could not recommend that method for a permanent improvement. They advised that permanent results could only be obtained by a stone training wall, four miles in length, across the shoals from Coney Island towards Sandy Hook, the estimated cost of the improvement by this means being £1,250,000, as against £270,360 for dredging only. Ultimately, after some successful experimental trials, the dredging was continued, and between 1884 and 1890 the channel was deepened to the required depth by suction dredging, at a cost of £258,551. The material removed was principally sand and alluvial matter. Thus by executing the work in both channels by dredging without training, an unnecessary expenditure of about £1,000,000 has been saved, and less time occupied in satisfactorily completing the improvement, and so sooner providing better facilities for the navigation. So far there have been no signs of shoaling taking place, although the bay has been visited by severe storms since the channel has been completed. An official report made a year after the work was finished, stated that there was then a continuous channel at low tide 1000 feet wide and 30 feet deep from the narrows to the

ocean. ("Improvement of the Channels at the Entrance to the Harbour of New York," J. Edwards: *Trans. American Society of Engineers*, 1891.)

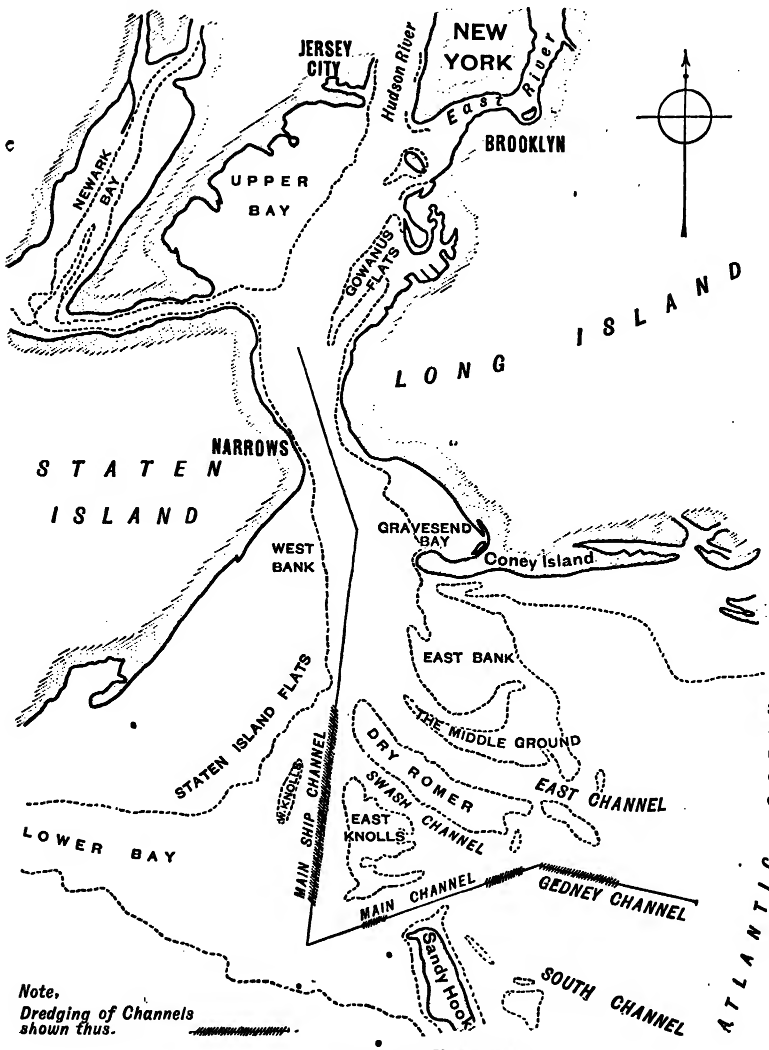


FIG. 24.—Plan of New York harbour.

On the coast of Belgium, the approach to Ostend has been improved by dredging a channel in the open sea through a large bank of sand called the Stroom Bank, running parallel with the coast. The channel dredged is 2000 feet wide and

10 feet deep at low water. No dredging has been done in this channel since the autumn of 1891, and the depth has remained practically the same. ("Maintenance of Ports on Sandy Coasts," P. De Mey: 1893.)

With channels consisting of a series of shoals and deep places, such as are frequently to be met with in estuaries, in situations sufficiently sheltered, these may be economically improved and deepened by removing the material by suction dredgers, and depositing the material through troughs or pipes on to the sides at a sufficient distance to prevent its washing back, or by depositing it from hopper barges into low places or subsidiary channels, and so assisting to concentrate the flow of the currents in one main channel.

By thus judiciously placing the dredged material, even if only sand, in the low places, the tidal water coming into the estuary may be trained and directed into the main stream.

Where dredging has to supplement training, the cost of the work may be very considerably reduced by carrying the works on simultaneously. Whether the training consist of stones or fascines, it is necessary to give considerable substance to the walls to prevent the work being carried away as the walls rise above the level of low water. The walls, which at first rise above the level of the sands, subsequently become buried by the material which accretes at the back, the face only being then of any service. As the wall is raised, if sand or other material to be removed from the channel be conveyed from the dredgers through troughs or pipes to the back of the new wall, this will require to be of much less substance, and the quantity of stone or fascines required be little more than is necessary to provide a facing. A place of deposit for the dredgings is at the same time provided at much less cost than if it had to be removed by hoppers.

Before, therefore, deciding on an expensive system of training walls, it is desirable to give due consideration as to whether an existing channel cannot be regulated, deepened, and improved by dredging alone.

Examples of various methods of improvement and the cost of the work will be found in the chapters on "Training and Dredging."

Conditions of a Tidal River in Good Order.—A tidal river in good order ought to fulfil the following conditions:—

1. The tidal wave at the foot of the tide should be propagated at a rate of not less than 10 miles an hour.

2. The level of high water should not be lower at the port up the river than at the mouth.

3. The duration of the tide—that is, from first of flood to high water—should not be less than from 4 to 5 hours.

4. The velocity of the tidal current should not exceed $2\frac{1}{2}$ miles an hour.

5. The depth at low water should be sufficient for the navigation of the ordinary craft frequenting the port, and at mean high water allow 2 feet under the keel of the largest vessels.

6. The width should diminish from the mouth upwards, the progressive widths being greater in proportion at the lower end than the upper.

7. The channel should not have in it any curves of less radius than 2500 feet.

8. The section of the channel should be large enough to allow the upland water in floods to flow down at a velocity that will not materially interfere with the navigation.

CHAPTER IX.

TRAINING.

THE purpose to be attained in training a river is to fix the channel in one position, and to regulate its width so that the water shall flow without disturbance; and that the whole force of the tidal and fresh-water currents shall be concentrated in maintaining one deep uniform channel.

In a shallow channel running through an estuary where the sands are sufficiently mobile, the force of both flood and ebb is expended in rolling over immense quantities of material and forming fresh courses, the water being encumbered with the sand thus eroded and set free.

In a trained channel, in place of a wide, shallow body of water trailing over a series of newly formed channels, wasting its energy in rolling the sands about, the current becomes an energetic agent, doing good work in the right place. By guiding the first of the flood and the last of the ebb by means of training walls, the strength of the current operates in the same line of channel, and thus a much greater permanent depth is secured.

Effect of Training on Estuaries.—There has been recently some controversy as to the effect of training walls, and it has been urged that training tends to accretion, and so diminishes the capacity of the estuary and the quantity of tidal water passing in and out; and that it may have a damaging effect on the outfall of the channel where it empties into the sea, and may tend to the shoaling of the water over the bar where one exists, or even be the means of creating one. This theory was put forward very prominently by the opponents to the first scheme, proposed by Mr. Leader Williams, for the approach to the Manchester Ship Canal through the upper estuary of the Mersey, which consisted of training and guiding the water in

one main channel, instead of allowing it to wander all over the estuary.

Sufficient allowance does not appear to be given by those who raise this objection to the fact that training does not create material. Mr. Stevenson ("River Engineering") says on this subject, "It is difficult to conceive in what way parallel training walls formed in an estuary can operate either in bringing down additional alluvial matter from the river above, or in bringing up additional detritus from without the bar. . . . The tendency of works of this kind is not necessarily to produce additional accumulation, but simply to alter the disposition of the existing materials of which the bed of the estuary was originally composed. . . . Even if a deposit does take place, the compensation afforded to the navigation by well-designed works is very much greater than is generally supposed." He shows that this was the case in the river Lune, where training walls had been put in. Very careful observations showed that, while an accumulation of sand had taken place in one part of the estuary on account of the training, in other parts the sands had lowered to an equal degree.

Accretion and Reclamation.—Training may lead to a new disposition of the sands, accumulation in one place being compensated by denudation in another, the tidal area remaining the same, and the condition of the estuary may be improved by the water being less encumbered by the moving sand.

Even allowing that training may be the means of arresting some of the alluvium brought down by the river, which otherwise would have been carried out to sea, this will be fully compensated for by the increased volume of water gained by the deepening of the channel. The training and consequent raising of the foreshore may also be the means of checking erosion which has been acting on the shores.

The result of preventing the constant shifting of the sands also allows the surface to become coated with grass or other marine vegetation, and by this means preventing the action of winds in disturbing the sand and allowing it to be carried off by the ebb from the foreshore into the channel.

The accretion consequent on training frequently leads to reclamation, portions of the estuary being enclosed, thus diminishing its tidal area. The effect of reclamation in its damaging effect on the outfall of rivers has, however, been much over-rated.

The Tidal Harbour Commissioners, who were appointed about fifty years ago to investigate the condition of the harbours and tidal rivers of this country, seem to have started with the fixed idea that any enclosure from a tidal area must necessarily damage the outfall of the river, and the bad condition of many rivers was ascribed to this cause, when it could be clearly traced to other sources. The unqualified opinion expressed by these Commissioners appears to have become stereotyped, and has since been adopted by many engineers without a due consideration being given to all the local circumstances that may prevail in an estuary. For example, the river Dee is universally quoted as an example of the damage caused to a navigable river by training, followed by reclamation. An investigation into all the causes which have operated in this river will show that no such lesson is to be gathered from its condition. As a matter of fact, it became and has remained in far better condition as a navigable waterway, and has a greater depth of water than it had before the works were carried out, and the depth over the bar has not diminished. It is true that the improved depth anticipated and promised when the works were laid out has not, until quite recently, been fully realized. The cause of this was due, however, to the fact that the water was driven out of its natural direction into a long straight channel, terminating in abrupt bends at one end, and in a bed of shifting sands at the other; that this channel was made too wide in proportion to the area which the river drained; and that consequently the current of the fresh water was not sufficiently concentrated to give it the necessary scouring power. No attempt was made to assist the removal of the sand in the channel by dredging, and the free run of the tide was, and is still, interfered with by a weir across the river.

The estuary of the Seine has also been quoted as an example of the ill effect of reclamation following on training, it being contended that, owing to the diminution of the tidal receptacle by the land enclosed, the scour has been weakened in the estuary below the training walls, and the deposit of sand has consequently increased, and that this may ultimately have an injurious effect on the scouring action of the tidal water in maintaining the sea channels. A careful investigation of all the conditions, however, shows that in this case, as in others, the apparent increase of deposit is merely a redisposition of the sand;

and that, as a matter of fact, the channel seawards of Havre, where an obstruction from a bar would exist if anywhere, has really deepened considerably; and that, although the navigation of the lower estuary is difficult owing to the shifting channels, yet this is no worse than it was before the training walls and reclamation were effected, and any alteration that has taken place is for the better.

That large areas of open estuary are not necessarily required for the maintenance of a tidal river is evidenced by the fact that the rivers in this country in the best condition for navigation, such as the Thames, the Humber, the Severn, and the Forth, have no such open receptacles for the tidal water; and that reclamation does not necessarily injure a river is shown by the fact that in the Humber, by the enclosure of nearly three-fourths of the whole estuary at different times, no injury has resulted to the channel, nor has the absence of the water that used to flow over this area resulted in the formation of a bar at its mouth. In fact, the reclamation of this land has improved the form of the river, and a channel sufficient for large vessels exists for nearly 50 miles from the mouth without the aid of any artificial training works. On the Thames the tidal water is now excluded from a very considerable area of land over which it once flowed, by enclosures made in the previous century, without injury to the channel or the outfall into the sea. The fact, however, should not be lost sight of, that this abstraction of tidal area has been compensated by extensive dredging and the removal of obstructions to the tidal flow. Nearly 70,000 acres have been reclaimed from the Wash since the construction of the Roman banks without creating any bar in Lynn Deeps, or, as far as known, diminishing the depth of water there or in Boston Deeps. Large reclamations of land have been made from the estuary of the Severn without decreasing the depth of the channel or its navigable facilities. In the Tay, from surveys made by Mr. D. Cunningham, it was found that, although the tidal area had been diminished by accretions in the upper part of the estuary, yet, owing to compensation effected by other improvements, the volume of tidal water had been increased and intensified in action, the channel improved, and the depth over the bar increased. On the Tees upwards of 2600 acres of land have been reclaimed as a consequence of the training works, but it has never been contended that this reclamation has in any way injured the

navigable channel or prevented the deepening of the water over the bar. The tidal water has now a longer, deeper, and more concentrated flow which more than compensates for the abstraction of any tidal water from the estuary.

Training and consequent accretion may be prejudicial if it results in the exclusion of tidal water which formerly found its way into and fed the ebb current in the main navigable channel and exerted a scouring influence at the outfall, and so was effective in arresting the formation of a bar, or of deepening the water over it. But if the tidal area consists of a bed of loose sand, through which shallow channels are continually shifting their position, and from off the surface of which the ebb current conveys into the channel large quantities of this moving material, far more harm is effected than the scouring effect can do good. If, however, as a consequence of accretion, the area becomes coated with vegetation, the water running off the marshes and out of the creeks, especially during the last of the ebb, may be a valuable feeder to the ebb current, if it finds its way into the main channel.

On the turn of the tide, the great mass of water in an estuary sets towards the ocean. As the velocity in the main deep water channels increases it draws towards it the water from the sides, and the channel is fed by the lateral supply; thus the volume passing out over the outfall is increased. Water that merely flows into and out of an estuary over the sands without going along the main navigable channel, cannot be of any assistance in keeping this channel open.

The vital point for consideration is not the mere retention of the water area, but the preservation of all that part of the estuary the water from which has a direct influence on the low-water channel of the outfall. A long length of tidal run up a deep and defined course, is of far more value than tidal area in an estuary. In the one case, the whole of the tidal flow passes up and down one course, and through the outfall to and from the sea. In the other, a very large proportion passes in and out of the estuary without ever entering the channel, or having any influence on the outfall.

By enclosing indents and irregularities in the coast-line the form of an estuary may be greatly improved, but in permitting the exclusion of tidal water, care must be exercised that such action does not unduly cramp its access from the sea, and space

should be allowed for this beyond that required for the low-water channel.

In an estuary of the form shown in Fig. 25, the enclosure of the marshes at AA and AB by a bank, shown by the dotted lines, would improve the form by cutting off the indents and irregularities, which allow the tidal water to expand unduly at

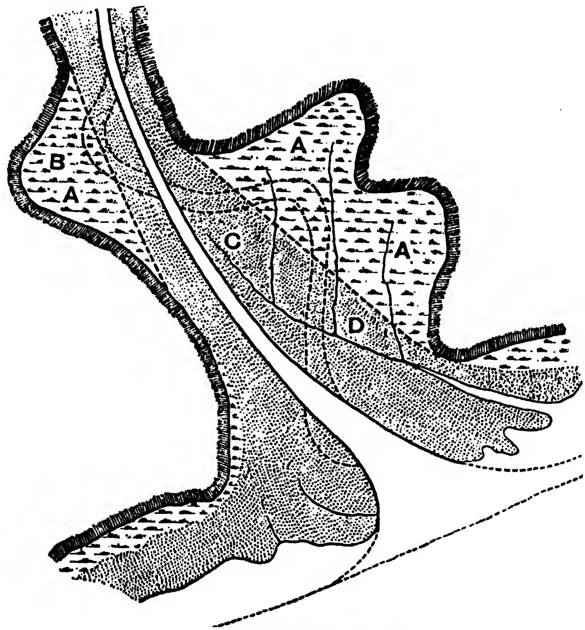


FIG. 25.—Plan of an estuary.

the upper end, and thus bringing the form of the estuary to a gradual and regular widening out towards the sea. The enclosure of the marshes at AA would only exclude tidal water which finds its way to the sea over the sands or by the creeks D, the keeping open of which might lead to the splitting of the outfall channel into two parts at C.

The conclusions arrived at by the section devoted to tidal rivers at the International Congress on navigation held at Paris in 1892, was, that "The regulation of the banks of tidal rivers, so as to remove abrupt variations in width equalizes the tidal flow, reduces accretion, and facilitates the tidal influx, and therefore constitutes an important means of improvement, even if accompanied by a slight reduction of tidal capacity at certain

parts by the obliteration of indents, which is generally more than compensated for by the improved scour, and consequent lowering of the low-water line, especially if accompanied by the removal of shoals."

Groynes and Parallel Walls.—Training may be effected either by groynes running out from the shore at intervals, by parallel walls, or by a single wall. For deepening the water at the outfall and over the bar, converging walls running out from the shore and contracting the entrance and outfall of the tidal water have also been adopted. Parallel walls are the most effective and permanent way of training rivers. Groynes placed at right angles or obliquely to the channel may, however, be used in some cases with advantage. When a river is very wide, or winds very much, the current may be diverted and gradually brought to the intended line economically and with little disturbance to the navigation by groynes. After the channel has been directed to its new course by this means, an accumulation of the sand disturbed will rapidly take place between the groynes. When this has taken place the ends can be joined together by parallel walls, the depth to which these will have to be carried being considerably diminished by the filling up by the action of the groynes of deep gullies and holes crossing the line of the training, and by the surface of the ground at the back of the walls being raised before the building commences.

In forcing the current in a new direction by training walls, a very heavy scour frequently occurs, especially at the end of the wall crossing the direction of the old channel. The sand is rapidly washed away and a deep hole formed, which follows the training wall as it advances. This absorbs a very large amount of stone, nearly the whole of which afterwards becomes buried. Thus in the training works for rectifying the bend in the river Ouse below Goole, although the average height of the walls did not exceed 12 feet, yet for a considerable length they extended from 30 to 40 feet below low water. By first directing the channel into the intended new course by groynes, this difficulty is avoided, and less material is used if the groynes are extended gradually, and the channel coaxed rather than driven into the new course.

The method of first directing the channel by groynes was adopted both on the Clyde, the Tyne, and the Tees, and also on the Danube.

On the Clyde, the channel was first regulated and brought to its intended direction and a uniform width by means of stone groynes or jetties carried out from the shore, upwards of two hundred of these, varying in length from 50 to 550 feet, being placed between Glasgow bridge and Bowling. After the space between these jetties had become filled up, the ends were joined together by low rubble walls. All appearance of these groynes and parallel training walls has now disappeared, and the river for a great part of the way flows through land above the level of high water. The banks have slopes of 1½ to 1, and are covered with whinstone rubble. This was formerly hand-pitched at a cost for labour alone of 1*s.* 2*d.* per superficial yard. The stone now is left as laid on, and it is found that the slopes stand better thus than pitched, and break the wash of the steamers more effectually.

The Tyne was trained and its width regulated by groynes running out from the shore at the wide places. The ends of these were, as in the Clyde, subsequently joined together by low rubble parallel training walls, the greater part of the material being obtained from the ballast brought by vessels coming for coal. The groynes were made of yellow pine timber, braced together with half-timber walings, and the spaces between the main piles filled in with 3-inch sheet piles. The average cost was £1 5*s.* per running foot. As the groynes were carried through shifting sands, a covering of chalk rubble, obtained from the ballast brought by the colliers, 9 inches in thickness for a width of 9 feet was spread on each side of them to prevent scour. The deepest part of the section, where the scour was greatest, was generally closed first. Similar groynes were found to be more advantageous than those constructed with stone or rubble, as they could be completed more rapidly and in the end were more economical.

The Tees, which had a very winding course through the estuary, was brought to a direct line by means of groynes. At Bamblets Bight the channel was directed from close in shore nearly to the middle of the estuary by three timber groynes each 1000 feet in length, connected from head to head by sheet piling. Subsequently a groyne was run out across the north channel for a distance of 1400 feet, and the current directed into the south channel. This groyne was formed of clay and stones for the first 900 feet, and then of timber, supported on each side

by clay and stone. The groynes first run out were afterwards connected together by longitudinal training walls.

The use of groynes has also an advantage, that the width of the channel may be regulated and determined by their aid before the permanent training walls are built. In the works on the Seine, the Maas, and the Mississippi, the width of the channels was found to be either too restricted or too wide, necessitating in the one case the pulling down of the walls already erected, and in the others the contraction by means of an inner wall or groynes running out at right angles from the wall.

Groynes as a permanent means of training cause irregularities in the flow of the water. Eddies and disturbances are set up at their ends, and also at points in the channel below them depending on their length. The velocity of the current is thus checked, and the propagation of the tidal wave disturbed by the water absorbed in filling the spaces between them.

Sea Outfalls.—In determining the position to be given to training walls in estuaries where they discharge into the sea, the direction not only of the flood and ebb tides and of the prevailing winds must be considered, but also the amount of material that is transported along the coast, and the direction from which it comes.

In some cases where there is much littoral drift, especially of shingle, the outfalls have been driven considerably to leeward. In such cases Nature appears to indicate that the water should be directed into the sea by a curved channel having its convex side presented to the direction from which the material is travelling, and that the training should be so designed that it may be extended further out seawards as the shore grows up with the accumulated material.

A straight channel, having its axis in the direction from which the heaviest gales come, is difficult to navigate, and liable to have its entrance blocked by material driven up in stormy weather. A channel in which a ship has to enter broadside to the heaviest prevailing gales is also difficult to navigate.

Where one stream joins another, the best direction for the junction of the tributary is by a gentle curve tangential to the main stream. If this rule were applicable to tidal channels entering the sea, the outfall should be by a curved channel leading in the direction of the main set of the flood tide along the coast. It will be found that some rivers in their natural

state, which have deep-water outfalls and no bars, comply with this condition. On the other hand, rivers will be found having their outfalls as favourably circumstanced which have mouths debouching into the sea at a sharp angle away from the set of the flood current.

Neither an examination of the outfalls of rivers in natural condition round this or other coasts, nor a study of artificially trained rivers, give sufficiently consistent results to guide in the laying down of any definite rule.

It may be accepted as correct that, apart from considerations of shelter and harbour works, the training walls of rivers should be raised sufficiently high to direct the flow of the water in the required direction and to prevent cross-currents, and that, to be successful, they should never terminate in shallow water. The direction given should be such as to draw the ebb and flood current without unnatural disturbance in one stream, and they should be so designed as in no way to throttle or impede the entrance of the tide.

Where training walls have not been carried out into sufficiently deep water, their effect has been short-lived. Acting as a groyne to stop the travel of the littoral drift, this has rapidly accumulated at the back, and then found its way round the end into the mouth of the river, forming shoals or a bar. Where the pier reaches the level of deep water, the sand or shingle is kept in continual agitation by the effect of gales and the tidal currents, and is either drifted past the entrance or out into the deeper part of the sea.

Single Piers at the Mouths of Rivers.—There are cases where a single curved wall, running out from the shore-line, has been sufficient to maintain a channel in the direction required. Such a wall placed on the windward side of the channel, or the direction from which the flood tide and the littoral drift come, and presenting its convex side to the line of drift, if carried sufficiently far out into deep water, will give under favourable circumstances a permanent direction to the flow of the water, and afford protection to the entrance from the prevailing gales. The jetty, acting as a groyne, will at first collect the littoral drift in the angle between the pier and the shore, but after this is filled up, the direction given by the convex form of the outer end of the jetty will carry the drift beyond the entrance and into the deep-water currents. The flood tide, working round

the end of the pier-head into the channel, as it does in the case of the natural pier at Spurn Point in the Humber, will tend to maintain at that point deep water, and prevent the deposit of the littoral drift and the formation of a bar. The ebb current running along the concave side of the jetty will maintain the deepest water along that side of the channel, the flood tide setting up also along the line of deepest water. A uniform and deep channel may thus be maintained. If the line of direction be well chosen with regard to existing circumstances, a single wall will therefore be sufficient to maintain a channel in a uniform direction and preserve deep water. There are several examples where single walls thus carried out have been successful.

Before, however, deciding on the direction to be given to such a training wall, the fullest local information should be obtained as to the natural set of the currents and the direction from which the gales come which most interfere with the approach to the river.

Converging Piers.—Training walls running with the stream and gradually opening out to the sea are a more effective and permanent method of improving the outfall of a tidal river than those which are carried out from the land and converge, leaving a narrow opening. The former bring the river into a condition conformable to the teaching of Nature; they afford a better approach for the navigation, cause less disturbance to the tidal flow, and have the advantage that they can always be extended if the necessity arises. Professor Haupt, in a paper on "Jetties and Harbours," in the 99th volume of the *Minutes of Proceedings of the Inst. C.E.*, says "that he has been unable to find a single instance in America where convergent jetties have resulted in securing permanent improvement."

With converging piers the effect is too local, and, if resulting in scouring out a deep hole in the immediate neighbourhood of the pier-heads, there is a tendency for a shoal to form at a short distance away. The velocity of the current both within and without the walls not being in accord with that of the general flow of the river, it might naturally be anticipated that local scouring action and deepening in one place would result in shoaling in another, and that a bar removed by this action would form again at a short distance outside the piers. The passage of a large volume of water through a narrow opening,

expanding into a wide area inside, is not favourable to the propagation of the tidal wave, and the rapid current set up through the pier-heads makes navigation, except at high water, difficult and often dangerous. It is very undesirable, in the interest of the navigation, to give the flood and ebb currents a greater velocity than is necessary to keep the channel of the river or outfall clear of deposit.

In the case of the Tyne, one pier projects abruptly from the shore, the south pier running more in the direction of the channel, the two converging towards the entrance. But these terminate in deep water, and form a considerable projection from the coast-line. These piers cannot be regarded as mere training walls, but were designed to afford within their shelter a harbour of refuge from the storms of the North Sea.

The piers carried out by Sir J. Hawkshaw in the North Sea, for the protection of the entrance to the Amsterdam Ship Canal, converge from the shore to the entrance, and project about a mile from the shore. They are so designed as to concentrate the

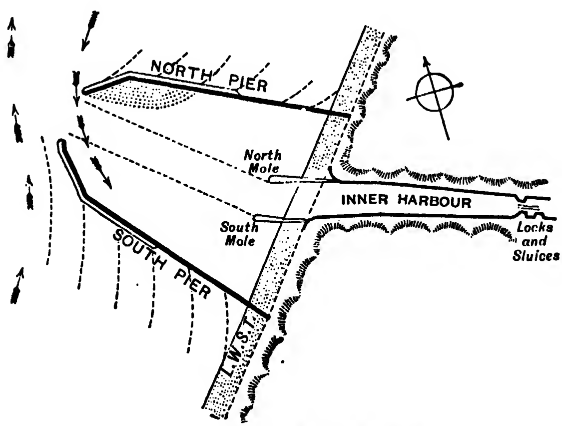


FIG. 26.—Entrance Amsterdam Canal.

scour of the water on the entrance. In this case, however, the flood and ebb channel is directed along the line of channel in the centre by low jetties, the space between the piers forming a tidal reservoir. The coast-line is regular, and the natural set of the currents parallel with the shore, and their velocity from 2 to 2½ knots, the rise of tide being from 7 to 10 feet. The effect of the projecting piers has been to deflect the coast currents in the direction shown by the arrows in Fig. 26, the littoral drift-

sand accumulating behind the piers in the manner shown by the dotted lines. The velocity at the end of the piers was increased by the piers to 3 and with some winds 4 knots. An eddy current enters the harbour, setting towards the south pier and creating the sandbank shown in the illustration. The land water from the canal and the tidal water which fills the basin keeps the entrance scoured (Mr. H. Hayter's remarks, the paper on "Bars," *Min. Proc. Inst. C. E.*, vol. c.).

The Liffey may be more appropriately quoted as an example where converging piers have been carried out for the purpose of deepening the channel and scouring away the bar. In this case one pier runs parallel with the axis of the channel, and the other meets it at an angle of about 45 degrees (see Fig. 27). Sufficient

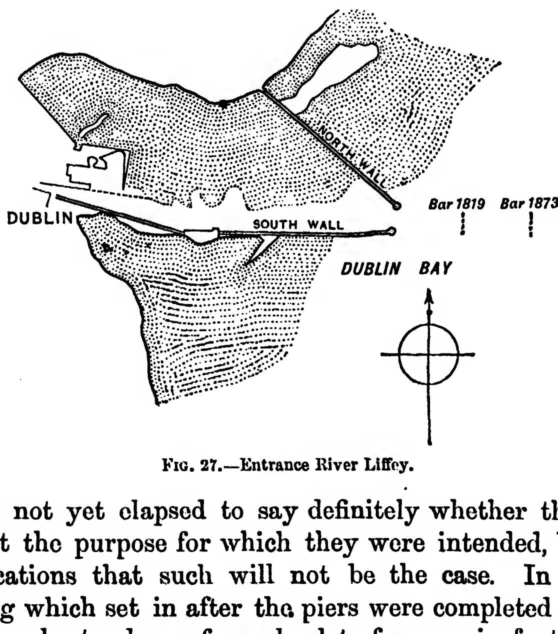


FIG. 27.—Entrance River Liffey.

time has not yet elapsed to say definitely whether these piers will effect the purpose for which they were intended, but there are indications that such will not be the case. In fact, the deepening which set in after the piers were completed has been arrested, and a tendency for a shoal to form again further out is manifested.

Extension of Piers to Deep Water.—Where it is contemplated to run out jetties into the sea at the mouth of a tidal river in order to remove a shoal or bar, the risk of the gradual growth of the shore-line seawards until it progresses as far out as the pier has to be considered. Thus for the protection of the harbour of Lowestoft, situated on the flat shore of the East Coast, piers were

built out from the shore-line. The windward pier, or that on the side from which the drift came, acted as a groyne, causing the sand and shingle to accumulate at the back and to extend a considerable distance out from the shore. The harbour entrance is separated from the main channel of the North Sea by a long ridge of sand which runs parallel with the coast for several miles, the approach being by an opening through these sands. On the land side of the piers is a large tidal basin, and the river Waveney discharges into this basin. The rise of tide is about 6½ feet. The shingle is constantly working its way round the end of the north pier into the harbour, necessitating constant dredging to maintain the depth. In north-east gales a bar also forms across the entrance, interfering with the navigation. In this case the jetty does not extend sufficiently far out to prevent the shingle travelling round the end, or to make the velocity of the littoral current sufficient to carry it past the pier-heads. The accumulation of shingle having now extended out from the shore past the piers, there is always at hand a constant supply of material for the littoral current to carry into the harbour. This could be prevented by arresting the travel of the shingle by a groyne carried out from the Ness, which projects from the coast-line about three-quarters of a mile to the north of the harbour entrance, and which could be extended from time to time as the material accumulated at the back. This would at the same time provide a shelter to the approach to the harbour from north-east gales, the narrow space between the pier-heads being difficult to make in strong gales.

The river Adour affords another example. The outfall of this river is into a part of the Bay of Biscay where the shore is shallow and sandy, and where the rise of spring tides is only 8 feet. Piers were carried out along both sides of the outfall in order to contract the entrance, with the object of scouring away a shoal of sand which existed at the mouth. The result was that, when the piers were completed, the shoal was scoured away only to reform further out. The accumulation of sand which takes place outside the piers which have been constructed for the improvement of the harbours at Calais and Dunkirk on the north coast of France, shows that the mere extension of piers from the shore is not sufficient to secure a deep channel.

Height of Training Walls.—The height to which training

walls are carried in an estuary must depend on their position and circumstances. Their main object being to direct the low-water current, it would seem that if they were carried up as high as the highest level of low water it would be sufficient; but experience shows that they are not in the most effective condition unless carried as high as half-tide level, that is, at a level equal to a mean between high and low water of spring tides in the open estuary. Walls which are at a less height than this allow cross-currents to prevail, which detract from the advantage obtained from an even flow along the axis of the channel. While walls that are too low do not sufficiently direct the tidal currents in the true line, high walls cause accretion and prevent the lateral spread of the tidal water. Objection is frequently raised to low walls that they allow the sand to be washed off the foreshore into the channel. This, however, is an objection that cannot hold good. Even if sand were washed off after the first formation of the walls, this would cease as soon as the sand had obtained a natural slope, and any sand washed off after this could only be from material carried on by the tides. As a matter of fact, the objection amounts to this, that low walls do not favour accretion as rapidly as those carried to a higher level. As far as navigation is concerned, walls carried to half-tide level are the safest. Fishing-smacks and boats of light draught are apt to run their stems on low walls when they are covered at high tide and become fast, receiving injury from the position in which they will lie when the tide falls.

When training is carried on above the open estuary, and where a lateral expansion of the tide is prevented by embankments, a berm should always be left for the expansion of the tide as it rises above the level of the walls. By this means, while keeping the ebb current within the limits best adapted to develop its scouring power, a receptacle is provided which ensures a sufficient provision for supplying scour to the outfall, and the propagation of the tide is less throttled.

Method of Construction.—The method of constructing training walls varies considerably. In certain situations a very slight bank is sufficient to give the intended direction to the current. In the account of the works carried out for directing and rectifying the river Vire, which discharges into the estuary or Bay of Vays on the north coast of France, given by M. Bouncieau in his work on the "Navigation of Tidal Rivers," the following

method is described. The soil through which the channel was to be diverted consisted entirely of alluvial matter lying above the level of low water. Along the direction of the intended channel low mounds of sods obtained from the salt marshes were laid, leaving a sufficient distance between them for the ultimate full width of the channel. These mounds were covered with stone, the quantity used increasing as the channel approached the more exposed parts of the bay. A trench was then cut by spade labour along the centre line of the intended channel. The ebb water of the marshes on the receding of the tide was directed into this channel, which was then gradually widened by the scour until a fair-sized channel was obtained. The old course was then gradually dammed up, and the water diverted into the new course. The scouring of the new channel was aided by harrows and by scouring-dams formed by boats. When the channel reached the mounds, the stones placed on the sides fell at an angle which formed and covered the sides, new stones being added where required. The thickness of this covering varied from 18 inches to 3 feet, being thicker at the base than at the top.

Bags of sand may also be used for training purposes. In a case which came under the author's experience, where it was intended to open out a channel across a sandy foreshore by scour caused by discharging the water from a new cut which had been excavated through the land, the contractor controlled the direction of the flowing water in the course desired by bags of sand, and succeeded by this means in removing the greater part of the top covering of sand to a depth of about 5 feet, and opening out a channel down to the hard ground, which he was able afterwards to complete by dredging.

Sand-bags may also be effectively used where it is desired to shut off lateral creeks from a main channel in a sandy estuary, and for correcting sharp bends; and generally in directing and improving the course of the low-water channel. In using these as dams care must be taken not to raise the dam too high, otherwise an overflow is created which sets up a scour and washes the dam away. A single bag in height is sufficient at first, gradually increasing the height as the sand accretes. A channel may by this means be brought into line, and afterwards, if found necessary, faced with stone at considerably less cost than by the use of stone training banks.

For diverting the channel of the river Don, groynes made of bags filled with sand were used. The groynes were made in the form of triangles. The sacks were laid lengthways, and from one to four sacks high according to the strength of the current. 7500 bags were used in one groyne. Fifty sacks measured 343 cubic feet, and cost deposited in place £2 6*s.*, equal to 3*s.* 2½*d.* per cubic yard. The sacks used were grain bags made of bass matting.

Fascine-work.—Fascines have been very extensively used for training work. The fascines used for training the outfall of the fen rivers on the East Coast are made of branches cut from thorn hedges. They are tied in bundles about six feet long, including the brush, and three feet girth by tarred string. These faggots are locally called "kids," and cost about 14*s.* a hundred (120) delivered on the banks of the river.

Where the training wall has to be laid below the level of low water, the fascines are conveyed to the site on barges, two barges of faggots being moored in the river in the line of the wall and parallel with it, and one barge across the end loaded with clay or marsh sods. At low water the fascines are placed in the water transversely to the jetty, overlapping each other one-half the length of the faggot, and covering a space equal to the intended width of the jetty. Each layer is weighted with clay or sods till it sinks, being directed to its place by boat-hooks fastened in the ground. This is continued until the jetty attains half-tide level. The wall is made as far as practicable to a batter equal to six inches horizontal to one foot in height (Fig. 28). Jetties constructed in this manner have been put in where the depth of water at low water has been 20 feet, and where there has been a tidal run of 4 knots, and have remained in position without repair since they were constructed twenty years ago. The sediment rapidly accumulated on the land side of the jetty, and in the course of a short time the fascines only formed the face of the channel, but there has always been a depth varying from 10 to 15 feet on the river side at low water. Thorns are well adapted for this work, as the branches interlace and hang together in a way that is not common to other brush-wood, and, the spaces between the branches becoming filled with soil and sand, make the jetty a very tough and solid mass difficult to remove. Fascine-work of this character has the advantage over stone in its tenacity, and the way in which the whole mass hangs together. If built on sand which afterwards scours out, it will

settle down in a mass and only require additional fascines putting on the top to bring it to the original level. The training of the river Ouse through the Vinegar Middle sands was effected thirty-five years ago by fascine-work of this character. In this case it was protected on the face by rubble stone, to prevent the faggots

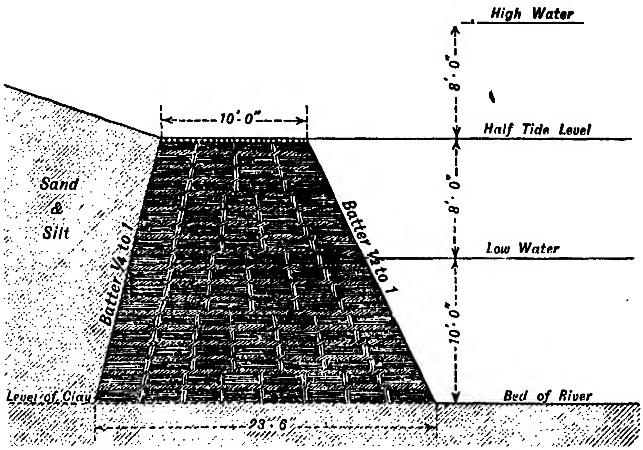


Fig. 28.—Section of fascine-work.

being washed up by heavy freshets or torn from their place by ice. These walls have stood without repairs for a great number of years. The Nene, the Witham and the Welland have all been trained in a similar manner.

The cost varies with the distance the material has to be taken and the quantity of stone used. A pier carried out by the author, where very little stone was used, cost 1s. 8*d.* per cubic yard. This pier was 16 feet high, with base of 22 feet, and top 13 feet, the cost per lineal foot being 19*s.* 3*d.* The details of the cost were as follows per hundred fascines:—

	£	s.	d.
Fascines, per 120	0	14	6
Conveying by boat five miles	0	4	0
Labour building jetty	0	3	0
10 tons of clay, 1*s.*	0	10	0
Stone for top, ¼ ton, 6*s.*	0	1	6
	1	13	0

Or allowing 70 fascines to a lineal foot, gives 19*s.* 3*d.* per foot run for the jetty. The clay was obtained from a scarp at the mouth

of the river. ("Fascine-Work at the Outfall of Fen Rivers," by W. H. Wheeler, *Proc. Inst. C.E.*, vol. xlvi. 1875.)

Fascine-work of thorns is well adapted for protecting the sides of channels from the erosion of the current, or the wash caused by steamboats; or to prevent them slipping into the channel where the same has to be deepened by dredging. For this purpose the author has used them in a tidal river. The usual way of executing this work is to commence by excavating as far below low water of spring tides as practicable, a slight dam of earth being left between the excavation and the water. From three to four fascines are then laid in, overlapping each other, and with their butt ends at right angles to the channel, the outer layer having the brush end towards the water. On this a layer of the excavated soil is placed, and then another row of fascines, the process being continued until the top course is brought up to the level of ordinary high water, the depth of the courses of fascines gradually being diminished till the last finishes up with a single fascine. The brush is then trimmed off to a neat face. Provided that plenty of clay or similar material is used, this work is of a permanent character, any interstices of the fascines becoming filled with silt. Fascine-work executed in this manner in the fen rivers fifty years ago is still in good condition.

Fascine-work is used very extensively in Holland for training rivers and for making dams for closing channels which require to be diverted. The fascines are composed of willow, alder, or brushwood of similar character to that which grows in the swamps. The fascines are made into bundles from ten to eleven feet in length and fifteen inches in circumference, the sticks of which the faggots are composed being about 1¼ inch thick at the root end. They cost from 5s. to 7s. per hundred. These fascines are termed "ryshout," and are made up into large masses or mattresses varying in size, the largest being 80 feet wide and 150 feet long, and about 1·66 foot thick. They are constructed in the following manner. The bundles of faggots are laid out on light frames supported by stakes driven into the ground the full width of the intended mattress, the sticks of which the bundle is composed being drawn out so as to break joint. They are then tied together in a continuous bundle about six inches in diameter with osiers at intervals of 15 inches, and by lighter bands between, so as to form a rope, or "wiepen." These bundles are then laid on the ground in parallel rows three feet apart, to the full length

of the mattress. They are crossed by a second layer of wiepen at right angles, forming a network with meshes three feet square. Every alternate layer is tied with half-inch tarred rope. This framework is then covered with three layers of ryshout placed in alternate directions, the three layers being 18 inches thick. A network of wiepen similar to the lower one is then again laid over these, and tied down to the lower course by the tarred rope, which is brought up for the purpose. The mattress is generally built on the shore between high and low water, so that when completed it can be floated to its place. On arriving at its destination, it is loaded with stone at the rate of from a third to half a ton to the square yard. To prevent the stone falling off as the mattress is being sunk, the upper surface is sometimes divided into rectangular cells by stakes, or "palen," driven into the crossing of the wiepen and round the edges. Between these branches are interwoven, forming wattlework or "tuin latten." The lower layer of mattresses is termed "grondstuken," or ground piece; the next layer "zinkstuken," or sinking piece. The mattresses are held in place by piles driven through the mass into the ground below. The thickness of each mattress is 3 feet 3 inches, and the cost about 2*s.* 6*d.* a cubic yard, or with the stone about 7*s.* per cubic yard.

The cost of fascine-work, as given in "Waterbouw Koude," by D. J. Stormbusijsing in 1854, is for mattresses placed below the water, and 1·64 foot thick, 29·24*d.* per square yard. For a

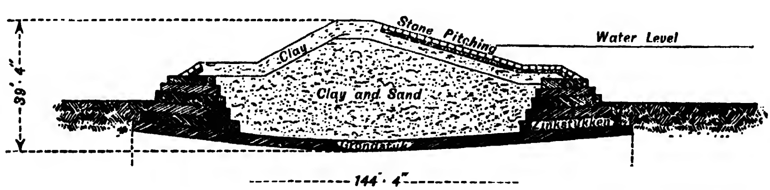


FIG. 29.—Fascine dam (Holland).

mattress 100 metres long, 10 metres broad, and 0·50 thick, the cost then was, for the fascine-work, £115·56, and for stone, £75·59. This is equal to about 6*s.* per cubic yard. Since then, however, prices have considerably risen.

When these mattresses are used for the construction of dams, the ground where the base of the dam is to be placed is first entirely carpeted with them. Two walls are then built up with mattresses, the space between being filled with earth (Fig. 29).

In soft ground the whole mass gradually settles until a state of rest is obtained, when the top is raised to the original level.

In closing the "Het Schœur" Channel, forming part of the works for the improvement of the Maas, several mattresses were used containing 2392 square yards.

The great dam across the Zuyder Zee at Schellingwoude, in connection with the North Sea Canal, was made with fascine mattresses on the exterior sides, filled with earth in the middle. The length of this dam is 4460 feet. The slope of the sides is ¾ to 1 on the outside, and 1¼ to 1 on the inside. The average section was 32 feet high, 131 feet wide at the base, and 13 feet at the top.

The piers for directing the outfall of the Maas into deep water in the North Sea were constructed entirely of fascine-work made in the manner described, protected by stone. These piers were found to be elastic, and little affected by the shocks caused by the impact of waves. They were also economical, and have been found after twenty years' experience to stand the wear and tear of the waves of the North Sea.

These piers were completed in 1874, and were designed and carried out under the direction of Mr. Caland, engineer of the Waterstaat. The north pier extends for 6560 feet, and the south pier 7544 feet. They terminate in a depth of 22 feet at low water, the rise of spring tides being 5½ feet. The width between the piers at the sea end is 2950 feet, contracted by a low wall to 2296 feet. The top of the south pier is about the level of ordinary high water, the north jetty being carried to half-tide level.

The pier, Fig. 30, was constructed in the following manner: The base course, or "grondstuken," projected 19·66 feet on

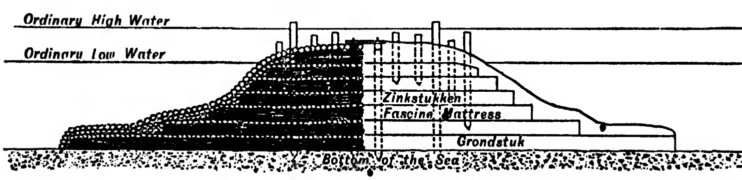


Fig. 30.—Pier of River Maas.

both sides beyond the course above it, and the second course had a set-off of 16½ feet. These "berms" were covered with stones, averaging half a ton each. Above these the wall was built with a slope averaging 1 to 1. The mattresses were 82 feet wide, and

of varying lengths, but averaging about 164 feet, and from 1 foot 4 inches to 1 foot 8 inches thick. The largest mattresses used had an area of 1674 square yards. The body of the pier took from 5 to 6 mattresses, averaging with the stones 3·33 feet thick. These were held in place by five rows of piles driven 12 feet through the mass into the sand below. The part above the water was covered with large stones, retained in their place by small oak piles, the ends of which project above the level of the work for the purpose of breaking the force of the waves. The top of the pier is 29 feet wide, and is made convex. The projection of the lower mattress at the sea end is 82 feet, and of the next layer 49 feet, both being well covered with stone. The entire cost of the mattresses, when deposited in place, including stone, averaged 11*s.* 3*d.* per square yard, or 10·13*s.* a cubic yard, the cost in this case being much increased by the difficulty in sinking the mattresses in the open sea. The cost of the piers, averaging 14½ feet high, was £38 9*s.* per lineal yard.

The construction of these piers has been a complete success, and is an example of an inexpensive method of training rivers out into the sea which may be safely followed on sandy coasts, especially where stone is scarce and materials for the construction of the fascines abound.

Further details respecting this work will be found in the report of Major Barnard on the "Improvement of the Navigation from Rotterdam to the Sea," in the professional papers of the Corps of Engineers U.S. Army, 1872; and the report of M. Desnoyers on "The Public Works in Holland" (Paris, 1874); also in the paper by Mr. T. C. Watson in the *Proceedings Inst. C.E.*, vol. xii., 1874.

The training and contracting the tidal channel of the river Weser from Bremen to the sea, a distance of 43 miles, recently completed, was effected by mattress-work. This river drains 18,000 square miles, has a rise of tide of 11 feet, and is now capable of being navigated by vessels drawing 22 feet. The training walls were constructed of fascine mattresses 66·58 feet long, 33·29 feet broad, and 3·28 feet thick. When made they floated 1·64 foot above the water, and were towed about 6 miles by small tugs to their destination. On being fixed in their place they were sunk with stones. The lower mattresses were 7·46 feet wider than those above, so that at each side they project 3·28 feet. The upper layer was made 14·76 feet wide.

The walls were left six inches above low water. This height was given to allow for the extension of the tidal water, and to ensure the walls against damage by waves and ice. The following quantities of materials have been used on the works: About 2½ million cubic yards of fascines, 2 million feet run of piles, 140,000 bundles of willows; 100,000 cubic yards of stone; 285 tons of galvanized wire, which made 1,235,000 cubic yards of mattresses and fascines. The cost per cubic yard for the finished work was 3*s.* 9*d.* per cubic yard for materials, and 2*s.* 8*d.* for labour, together 6*s.* 5*d.* a cubic yard. The stone cost about 6*s.* 8*d.* per cubic yard.

The jetties at the mouth of the Mississippi were constructed

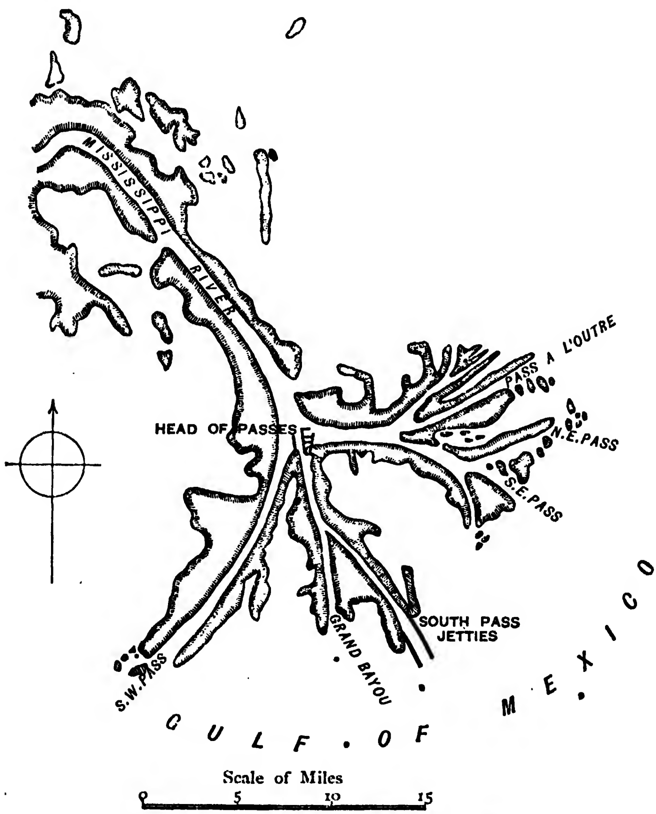


FIG. 31.—Plans of the mouths of the River Mississippi.

entirely with fascine mattresses. This river drains 1,200,000 square miles, and discharges in floods over a million cubic feet of

water a second, carrying with it 2000 cubic feet of solid matter. On approaching the Gulf of Mexico it is separated into three branches, and discharges its water by seven outlets, forming a delta which measures 15 miles in length and 2 miles in width (Figs. 31, 32). At the mouth of each pass is a shoal or bar. In the South-West Pass the depth is about 13 feet; at Pass A L'Outre, 10 feet; and at the South Pass, before the construction of the jetties, 8 feet. The delta advances into the Gulf at the rate of about 200 feet a year. Above the delta the channel is half a mile wide, and has a depth of from 50 to 200 feet. The rise of the tide, which does not exceed 1 foot 6 inches, is too small to have any effect in checking the deposit of material, which is continually going on.

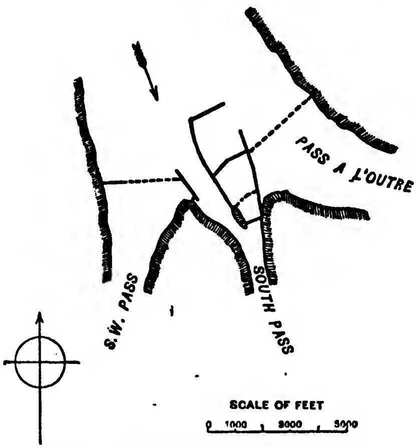


FIG. 32.—Plans of the mouths of the River Mississippi, enlarged.

In order to improve the depth from the sea into this magnificent river, which has a navigable waterway extending over 16,000 miles, General Eads advised the training of one of the principal outlets. His idea was that by confining the water within defined limits, and so increasing the velocity, the scour would become sufficient to prevent the deposit of the alluvium brought down, and to carry it into the deep waters of the Gulf of Mexico. He further undertook to carry out the works necessary to effect this purpose without receiving payment unless he succeeded in obtaining a channel 200 feet wide and 26 feet deep, with a central depth of 30 feet throughout. After very great opposition his offer was finally accepted, but he was compelled by the Government, against his own judgment, to operate on the South Pass, which was the smallest of the three main outfalls.

Before the works were commenced, the waters, on approaching the delta, began to spread laterally over the submerged land lying out in advance of the mouth, and, its current being enfeebled, it was no longer able to carry its load, and began to drop it upon

the bar, which, in the form of a half-circle, stretched entirely around the mouth of the pass from bank to bank. In the central portion of the outflowing water, the velocity of the current, being longer sustained, carried its load further, but finally dropped the heavier particles upon the crest of the bar or upon its outer slope, transporting the remainder out to deep water. The spread of the current as it issued from the land was like an open fan. General Eads closed this fan by constructing two parallel jetties running from the land out over the bar to the deep water of the Gulf, a distance of $2\frac{1}{4}$ miles. It was estimated that when these jetties were completed, it would require one hundred and twenty years before a new bar would be formed, if the circumstances remained the same; but, as at this outward point there exists a strong littoral current, it is expected that the sediment will be carried to a more distant part westward of the piers.

The slope of the bar going outward from the land inclined upward, for a distance of about $1\frac{1}{2}$ mile, at a gradient of 1 in 400; then there was a level area on which was from 8 to 9 feet of water at mean high tide, and then a downward slope of 1 in 60 into a depth of over 30 feet in the Gulf. At nine miles out the depth is 600 feet, and this continues to increase until a depth of $2\frac{1}{2}$ miles is reached. The statutory depth was obtained in 1879, and has been fully maintained since. Nearly the whole of the material required to be removed, amounting to over $7\frac{3}{4}$ million cubic yards, was carried away in four years by scour alone. The velocity of the current through the channel during floods was at the rate of three miles an hour, decreasing to $\frac{3}{4}$ mile at the ordinary state of the river. Dredging was only resorted to for the purpose of removing some stiff clay, and hastening the work in places. The total removed by dredging did not amount to one per cent. of the entire quantity.

A large part of the transported material has been deposited in the space at the back of the walls, and has extended the shore nearly a mile out, the surface becoming covered with reeds and grass.

The east jetty is 11,800 feet long, and the west 7800 feet, being curved to a radius of 15,000 feet. The terminal points in the Gulf are 1000 feet apart. The effective width of the channel through the jetties is about 700 feet.

In order to prevent the water escaping too freely through the other passes, it became necessary to place a sill or carpeting of

mattresses from the works at the head of the South Pass, and also entirely across the South-West Pass and Pass A L'Outre. These are shown by the lines on the plan, Fig. 32. These sills were built of mattresses 70 feet long, 30 feet wide, and 2 feet thick. They were laid side by side on the bed of the channel, with their length in a line with the axis of the current, so that they formed a carpeting 70 feet wide. A mattress dam was also placed across the Grand Bayou, which was 300 feet wide and 30 feet deep. By this dam the bulk of the water was directed to the channel through the new jetties.

The method of constructing the jetties was as follows: Guide piles were first driven along the line of the intended pier, and a carpet of mattress-work was laid in advance to prevent the scouring away of the soil as the channel became contracted. The mattresses used for the jetties were made of willows brought from swamps, the distances varying from 25 to 315 miles up the river. These were weighted with stone brought down the Ohio river from a distance of 1320 miles. The total quantity of these materials used was: willows, 592,000 cubic yards; stone, 100,000 cubic yards; gravel, 10,000 cubic yards; concrete, 4300 cubic yards; piling and timber, 12 million feet board measure. The plan of constructing the mattresses was different to that pursued in Holland. Along the bank of the head of the pass inclined ways were built at right angles to the shore, and extending back from the river 50 feet; these sloped up from the river about 6 feet. The timbers of the ways were spaced 6 feet apart. On these ways a framework of wood was first made, consisting of timbers 6 × 2½ inches laid across the ways for the full length of the mattress, 100 feet, and joined together by a cover piece 6 feet long. For a mattress 40 feet wide nine of these strips were laid on the frame; 1⅛-inch holes 5 feet apart were bored through the runners, and hickory pins, 30 inches long for a mattress 2 feet thick, driven in and secured by pins. The willows were then taken from the barges alongside, and laid on the frame in alternate directions in layers of 6 inches thick. Fir runners, similar to those used at the bottom, were then placed on the top and pressed down with levers, and held in their place by rods and pins driven through the hickory pegs. The mattress thus completed was then launched like a boat, and towed floating to its place along the line of the jetties by a steam-tug.

After being fixed in position, a barge loaded with stone was placed alongside, and the stone distributed evenly over the mattress until it sunk to the bottom (Fig. 33). The last mattress was built in its place on the jetty at low tide. One cubic yard of stone was used to about 5·32 cubic yards of fascines. At the sea end some of the mattresses subsided about 18 feet below the surface. The foundation course was from 34 to 50 feet wide, according to the depth of the water, the top diminishing to 25 feet. Along the line of the jetties wing dams were run out, extending at right angles into the channel, narrowing it from

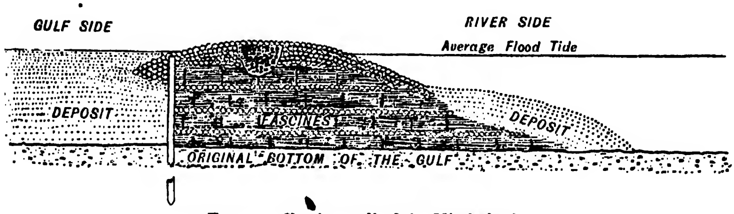


FIG. 33.—Fascine wall of the Mississippi.

1000 to 700 feet. The object of these was to locate the deep-water channel midway between the jetties, and to induce a deposit of sediment to protect the foot of the walls. These spurs were spaced 600 feet apart. They were built by driving a row of piles out from the jetty line, and resting mattresses on edge against them.

As the mattresses were fixed in place, the river deposited sediment amongst and behind them, raising the bottom of the gulf to their level, and securing the works against the waves, and rendering them impervious to the lateral flow and escape of the river water. The top of the mattresses was weighted with stone, and in the most exposed parts at the sea end of the east jetty, where the sea was the heaviest, with blocks of concrete weighing from 20 to 70 tons. During storms the waves were sufficiently powerful to remove the mattresses even when weighted with blocks of stone weighing from 1 to 2 tons. On one occasion, during a cyclone, concrete blocks weighing 28 tons were lifted out of their place.

The walls have subsided since their first construction 1·28 foot, but since they have become buried in deposit no harm has been done to them.

The scouring and deepening of the channel followed on with

the construction of the walls. Commencing from May, 1875, the distance between the 12-feet depth of water on the inside and outside of the bar was 4300 feet. In February, 1876, this had disappeared, and the distance between the 15-feet depth was 5900 feet. This had disappeared by the following April, and the 20-feet depth extended 9600 feet. This had disappeared in the following August. The distance then between the 26-feet depth was 11,700 feet, and this was gone in March, 1879. The whole length between the 30-feet depth was 12,000 feet, and this was all gone in July, 1879, when there was a channel 30 feet deep, with a minimum width of 45 feet from deep water in the pass to deep water in the Gulf, the channel varying in depth from 30 to 75 feet. The channel has gone on improving, there being now a good navigable waterway nearly 100 feet wide and 30 feet deep, with a depth of 26 feet over 240 feet. The annual surveys of the Gulf show that very little shoaling has been going on.

A detailed account of these works will be found in the "History of the Jetties at the Mouth of the Mississippi River," written by Mr. E. L. Corthell, the resident engineer; and abstracts of the reports of the Government engineers as to the condition of the channel and of the Gulf outside will be found in the *Proceedings of the Institution of Civil Engineers.*

A somewhat similar plan was adopted for the construction of the jetties at Tampico for removing the bar at the mouth of the Panuco. This river empties into the Gulf of Mexico seven miles below the city of Tampico, and drains 45,000 square miles. Between Tampico and the mouth the channel is wide and deep. The banks are 1300 feet apart, and there is a deep-water channel of 30 feet, a depth of 20 feet extending over a width of 800 feet. There is no delta, but at the mouth there was a bar composed of sand and fine shells. The depth on the crest of this bar varied from 6 to 10 feet. The distance from the shore-line to a depth of 22 feet in the Gulf was 7000 feet. In 1888 the Mexican Central Railway Company determined to improve the entrance to the river, and thus provide access for large ships to the fine natural harbour inside, and a connection between the railway and the sea. The works were entrusted to Mr. E. L. Corthell, who had carried out the Mississippi jetties for General Eads. Two parallel jetties, 1000 feet apart, were run out from the shore 7000 feet to the deep water of the Gulf, having a direction nearly

normal to the shore-line and directly so to the Gulf currents. The jetties are composed of fascine mattresses and stone similar to those used in the Mississippi, but not constructed on shore. A tramway connected with the railway was run out from the shore, and continued along the jetty as it advanced. The brushwood and stone for the mattresses were carried on this tramway to a movable trestle, on which they were built and dropped into their place, the piles being driven by an overhanging engine in advance of the work. As the works were carried seaward and the base of the jetty became wider, the trestles were also moved forward and widened, so that at the outer ends mattresses 84 feet in width and 5 feet thick were built *in situ* and dropped from the trestles. The bar has been almost entirely removed by the increased scour of the current, one and a half million cubic yards of sand having been scoured away by the current. Vessels which formerly had to anchor outside in the Gulf are now able to proceed up the river. The channel for nearly the entire length between the jetties has been deepened from 8 to 30 feet. Sand has accumulated on the flanks of the jetties, and on the north side, which serves to break the heavy seas that sweep across the Gulf and on to the jetty during gales, which are very heavy from that direction.

Similar works have also been carried out by Mr. Corthell in the Brazos river, Texas, under a charter obtained by a company from the United States Government in 1888, and have resulted in deepening the bar of this river. The Brazos drains 30,000 square miles, the discharge varying from 2000 cubic feet a second in dry weather to 60,000 in floods. The amount of sediment carried is very small at the low state of the river, rising to one in 400 in very heavy floods. The average width of the river in the last 20 miles before reaching the Gulf is about 500 feet, with a depth of about 20 feet. The river begins to shoal near the mouth, leaving only 5 to 7 feet on the crest of the bar in the Gulf, at a point 4000 feet from the land. The littoral current flowing westward, and the action of the waves upon the bar, have prevented the formation of a delta, the detritus brought down the river being carried off by the Gulf currents. On a survey of the outfall being made, it was found that the outer 18-foot curve was practically in the same position as it was thirty years previously, and this had been maintained in the face of ten million tons of sedimentary matter thrown out into the Gulf.

Before the works were commenced there was only 1½ foot of water across the line of the proposed channel, and the only channel out to sea was a crooked one, and in this there was a depth of only 5 feet. The jetties were pushed out across the shoal on the intended lines, and the channel closely followed the advance of the works. The jetties, which are 5400 feet long, and 4 feet above mean high water, give an effective width of 550 feet. They were built of brush made into mattresses and weighted with stone. The jetties were supplemented by short groynes built out at right angles for the purpose of producing deposit along the foot, and solidifying the fascine-work and protecting it from erosion of the flood currents. In the course of a very short time steamers drawing 16 feet were able to enter between the jetties and proceed to Velasco, four miles up the river. A depth of 20 feet will be ultimately obtained.

For training the upper part of the Mississippi near St. Cloud, where it is split up into a number of channels by a gravel bar, a fascine dam was used constructed in the following manner: The length of the dam was 2900 feet; the average height, 3·30 feet; and the cubic contents, 7225 yards. The fascines used varied in diameter from 9 to 18 inches, and in length from 15 to 22 feet. One row was placed across the bottom parallel to the current, brush ends upstream, and staked down. A single row was then placed lengthwise of the dam about 3 feet upstream from the butts, and staked through each bundle under it. Gravel was then filled in to cover the tops of the lower row and make a plane surface to the transverse fascines. The succeeding courses were placed parallel to the current, except where the dam was unusually high, when another transverse course was placed, care being taken to have at least one course parallel to the current when the dam was finished. The whole was covered with gravel carried horizontally about 6 feet upstream. The fascines constituted about 38½ per cent. of the mass. The cost was 9*s.* 9*d.* per lineal foot, or 4*s.* a cubic yard; 34 per cent. of the cost was for gravel, 24 for stakes and driving them, and 42 per cent. for making and placing the fascines. (*Trans. American Society of Civil Engineers*, vol. vi.)

For the improvement of the entrance of Galveston harbour, where was a bar with 11 feet of water, a pier was constructed 1200 feet long. Piles were first driven, and then a carpet of mattress-work was sunk with stones, and on this boxes made of

wood and basket-work 12 feet long by 6 feet wide and 6 feet high. These boxes were floated into position, and sunk by pumping in sand. The cost per foot run was 33*s*. The south pier was further extended by mattresses ranging from 120 to 60 feet wide, diminishing at the top to 15 feet. The cost per cubic yard of jetty was 12*s*., the stone having to be conveyed over 100 miles, and the fascines 50 miles.

The channel at the outfall of the Columbian river on the north-west coast of America was formerly very capricious in location and variable in depth. The depths were usually from 19 to 21 feet, and the channels varied in number from one to three, and in location through nearly 180 degrees from Cape Disappointment to Point Adams. There is now a straight out and in channel having a width of a quarter of a mile, with a depth nowhere less than 29 feet, and for a width of a mile 27 feet. The training works were commenced in 1884, and it is contemplated, when they are completed, to have nowhere less than 30 feet over the bar at low water. The rise of spring tides varies from 3 to 8 feet. The training works consist of a jetty rising 4 feet above mean low water, starting from Fort Stevens on the South Cape and extending in a westerly direction, with a slight curve to the south across Clatsop Spit for a distance of about 4½ miles. This jetty is constructed of stone resting on a mattress foundation about 40 feet wide, and from 2½ to 5 feet thick. The stone was placed in position by trucks running on a jetty tramway supported on piles driven along the line of the training wall 24 feet above the level of the water. There was a double track of 3-feet gauge. The effect of this training wall has been very marked in concentrating the water on the bar, and by increasing the scour in deepening the channel. Since the commencement of the work in 1884 there has been used 478,890 tons of stone. The cost of the tramway has been 27*s*. per running foot, and of the mattress-work about 18*s*. 9*d*. per lineal foot. Experience has shown that it is necessary to carry the wall to 4 feet above low water, as the first half of the tides flowing across the wall, either at ebb or flood, took the sand with them and scoured channels, especially where there were low places in the wall. It is only by raising the wall above low water that this can be prevented.

Stone Training Walls.—Training walls are frequently constructed of rubble stone, the stone being tipped into the water

in the line of the training wall, and allowed to take its own shape. This it generally does by assuming a slope of from 1¼ to 1½ to 1. It is difficult to estimate the amount of stone required. If much scour goes on, as in the case of the Ouse hereafter described, the base may sink to a great depth below low water. Where there is not much scour round the end of the walls, it has been found as a matter of experience that the stones do not settle below the bed of the channel. For the training walls on the Tees slag from the iron furnaces was very extensively used, clay being mixed with the slag at first, but this was found to be unnecessary. The ironmasters were also at the starting paid 3*d.* per ton for the slag, but subsequently they paid the commissioners 4*d.* per ton for removing the slag from their works. The walls were constructed by trains of punts 200 feet long, with loads of 100 tons, laid alongside a line of guide piles, driven about 100 feet apart. The slag was thrown into the water on the site of the intended wall until it was brought up to the required height. After the walls thus constructed had remained for a year and had taken their bearing, they were again made up to the proper level. These walls varied in depth from 12 to 40 feet, and rise from 4 to 7 feet above low water. They assumed a slope of 1 to 1 below low water on the channel side, but sank vertically in the sand at the back. Their total length, including cross-groynes, is nearly 20 miles, and their cost £50,000, varying as the square of the depth. (Fowler on "The Tees," *Proc. Inst. C.E.*, vol. xc.)

In the works carried out by Mr. Bartholomew for improving the river Ouse between Goole and Trent Falls, the training walls were made of slag brought from Middlesborough in steam-hopper vessels specially constructed for the purpose. Two of these carried 250 tons each, and the other four 450 tons each, the total cost of the six vessels being £50,000. The slag was delivered from the blast furnaces into the hoppers, and about two million tons was altogether used. On arriving in the Ouse, the vessels were moored to piles placed at regular intervals along the line of training, the hoppers opened, and the slag discharged on to the site of the wall. The height of the walls averaged about 12 feet, but in the sharpest part of the bend the river was scoured out to a depth of from 40 to 50 feet at low water. The top of the walls is about level with high water of neap tides, and varies from 4 feet 6 inches to 6 feet in width, the slope

being about $1\frac{1}{2}$ to 1. The result of the training was to deepen the river very considerably, a large amount of silt being scoured out from the channel. The walls were placed about 700 feet apart at the upper end, the width gradually increasing downwards.

The training walls of the Ribble were constructed of stone obtained from quarries up the river, which cost 3*s.* 5*d.* a cubic yard delivered on to the walls. In the lower walls a large quantity of red sandstone, obtained from the excavation of the dock, was used for this purpose. The cost of sorting out this stone, hoisting and placing it on the walls, was 2*s.* 3*d.* a cubic yard. The hard clay dredged out of the river was also used and deposited in the line of the training walls, being faced with stone above the water-line.

The training walls on the Seine were made of rubble chalk obtained from cliffs adjacent to the river. The chalk was tipped into the channel along the line of the intended wall from barges, and levelled to an even face above the low-water line. The top of the walls was made $6\frac{1}{2}$ feet wide, with slopes of 1 to 1 on the land side, and varying on the river side from $1\frac{1}{2}$ to 1 to 8 to 1, according to the force of the current. These walls were carried up to the level of high water. The chalk cost on an average 1*s.* $1\frac{1}{2}$*d.* per cubic yard in the bank.

Pile Work and Stone.—The method adopted for training the Sulina mouth of the Danube through the delta into the Black Sea, was by first driving piles in the line of the training and enclosing the space between with planking, behind which rubble stone was thrown up to the level of the surface of the water. Subsequently this temporary training was converted into a solid concrete wall, the rubble mound forming the base for the concrete. The piers were projected well beyond the line of littoral drift. The channel over the bar between the two lines of the jetties deepened by scour from 7 to $20\frac{1}{2}$ feet, which depth has since been maintained. Both in the Danube and the Mississippi the smallest branch was selected for training. In both cases, while the area of the new channel is ample for the navigation, there is less chance of the bar being formed again, as the amount of detritus brought down is considerably less than in the larger branches, and is therefore more readily transported away by the coast current.

CHAPTER X.

DREDGING.

ALTHOUGH in some instances a channel can be deepened by natural scour, yet where the material is hard, or where the quantity to be removed is large, dredging has almost invariably to be resorted to.

The simplest form of dredging is that where the material is only broken up, loosened, and disintegrated, and left to be transported out of the channel by the current.

In other cases, the material is pumped up or raised by buckets and discharged by pipes or troughs on to the adjacent land. Occasionally the material is discharged into barges, from which it is thrown into the place of deposit by hand; but in the great majority of cases the material has to be carried out to sea in hoppers, or the dredger itself both lifts and transports the material.

The amount of work done and the cost is generally calculated either by the weight raised and transported in the hoppers, or by the cubic contents of the hoppers. Neither of these results gives the actual cost of the work done in enlarging the section of the channel, as the quantity conveyed by the hoppers varies from the quantity as measured *in situ*, sometimes to a very large extent. In estimating the cost of dredging, the most convenient plan seems to be to calculate it by the ton conveyed, and estimate the relation that this bears to the material *in situ*, so as to arrive at an estimate of the actual cost of completing the required work. Where the material to be operated on is clay or stiff material, the relation between the quantity conveyed away and the quantity *in situ* may be calculated sufficiently closely to enable a fairly reliable estimate to be made, and, if desired, reliable contracts may be obtained based on the quantity measured from the sections as the work goes on, or before commencing and

after completion. In the latter case the contractor takes all risk of having removed material washed into the dredged portion of the channel. Where, however, the material is running sand or mud, it is not practicable to obtain estimates based on sectional measurements, and attempts made to do this have resulted in the contractors finding that the quantities have very largely exceeded the estimates, and they have either completed their contracts at a heavy loss, or been relieved from them.

The method of calculating the cost from the quantity carried by the barges is open to the objection that the weight removed includes a certain quantity of water, and that the result depends on the returns made by the captain of the dredger, the temptation naturally existing on the part of all concerned to make the quantity as large as possible.

Very little information is to be obtained from the various accounts of dredging operations as to the relation which the quantity transported away bears to the sectional enlargement of the channel, or as to that which a ton of material bears to a cubic yard.

Mr. Deas gives as his experience on the Clyde that quick-sand as taken from the buckets weighs 121 lbs. to the cubic foot. Mr. Fowler on the Tees found that sand weighed 112 lbs. to the foot, and mud 101·82 lbs. Clay is generally reckoned as weighing 109 lbs. per cubic foot. Taking sand at an average of 115 lbs., there would be—

	Cubic feet to a ton.	Tons in a cubic yard.	Multiplier to reduce cubic yards to tons.
Sand	19·47	1·38	0·72
Mud	22·00	1·23	0·81
Clay	20·55	1·31	0·76

When the material to be removed is soft mud, and a strong current running in the river, the quantity as taken from sections made from measurements of the channel forms no guide as to the quantity to be actually removed. Thus, in dredging carried out for improving the approaches to Grangemouth Dock, the sections showed 432,000 cubic yards as the quantity to be removed to deepen and enlarge the channel to the required dimensions. After dredging for eighteen months, 650,000 cubic yards, as measured in the barges, had been removed, but as measured *in situ* the quantity was found to be only 200,000 cubic yards. In dredging for the approach to the Albert Dock on the

Thames, the quantity as measured in the barges was found to be four times that measured *in situ*. In both these cases the material to be dealt with was soft mud.

In dredging for the new Ship Channel in New York harbour, an opposite result was obtained. The material dredged consisted of sand, clay, and mud, which, when it became agitated and incorporated with the water by the action of the pumps, settled so slowly in the barges that a portion went overboard, and was carried by the currents beyond the channel. The amount as measured in the barges was only 73 per cent. of that actually removed, as ascertained from the increased sectional area of the channel.

In dredging in hard boulder clay, the author found that 1·48 barge tons represented one cubic yard of material as measured from the sections of the river; and in dredging soft mud out of a dock by a Priestman grab into barges, he found that about 1·58 barge tons represented a cubic yard of material as measured by careful soundings as the work went on, the depth of the mud being 2·23 feet.

In Dunkirk harbour the difference between the quantity of material as measured in the section and in the barges varied from 25 to 45 per cent. according to the age of the deposit.

At Aberdeen, in dredging in clay with boulders, gravel, and mud, Mr. Cay estimated that one ton represented 18 cubic feet of solid ground, or 1½ barge tons to a cubic yard.

In dredging at the Sulina mouth of the Danube, it was found that a 100-ton barge with hopper capacity of 90 cubic yards represented 65 cubic yards measured *in situ*, or 1·54 ton to the cubic yard *in situ*.

Cost of Dredging.—The cost of dredging varies very considerably according to the circumstances under which the work is performed. Where a sufficiently large amount of material has to be removed to warrant the purchase of plant and the employment of a regular staff, dredging in sand can be done with screw hopper suction dredgers, including transport, wages, coals, repairs, and all expenses except interest and repayment for plant, at 1½*d.* per ton; with screw hopper bucket dredgers working in free material, at about 2½*d.*; and with stationary bucket dredgers and steam hoppers, the cost may be taken at about 3½*d.* With hired plant and for small quantities, the price will reach as much as 1*s.* 6*d.* or even 2*s.* per ton. The cost of dredging may be divided

into four principal items: the cost of raising the material, including coal and labour; transport; repairs and maintenance; and an allowance for interest on the capital outlay and the depreciation of plant. The item of interest may be taken at 4 per cent.; depreciation is generally reckoned at 10 per cent. on the cost of the plant. Repairs and maintenance are always included in the current expenses; they vary with the kind of machine, and may be taken at about one-third to one-fifth of the total cost of dredging and transporting for stationary dredgers and hopper barges, and less for hopper dredgers.

In addition to the actual cost of the repairs, there is also considerable loss of time in replacing the pins of buckets and other working parts of the machinery. This, however, may now be considerably reduced by the use of manganese steel. Pins made from this material used on the dredgers working at Preston showed a wear of only $\frac{1}{8}$ inch at the end of ten months, the ordinary steel pins previously in use lasting only about three months before requiring to be renewed. A cast-steel whelp on the top tumbler on a dredger used at the Hull and Barnsley Dock showed a wear of only $\frac{1}{4}$ inch in thirteen months, the cast-steel whelp previously in use having worn down $1\frac{1}{4}$ inch in the same period.

The cost is much increased when dredging has to be done in an open estuary, especially with stationary dredgers. Frequently during stormy weather operations can only be carried on for a few hours in the day, and during only a few months in the year, whereas in a wide river the work may proceed continuously day and night. In Carlingford Lough, although the machine was so constructed as to be able to lie at anchor on the site of dredging when not able to work, yet the working time during the three years the dredging proceeded varied from 67 to 131 days in a year. On many of these days the dredging could only be carried on for two or three hours.

The distance to which the material has to be conveyed has also a considerable bearing on the cost.

Where plant has to be hired, the cost of removing it from one port to another, including towing, insurance, etc., is very heavy. As an example may be quoted the figures given by Mr. Capper, as the cost of hiring dredging-plant from the Tyne for the improvement of Swansea harbour. This plant consisted of one dredger valued at £25,000 and five hoppers at £1500 each. The distance each

way was 800 miles. The towing cost £2000; insurance, £1554; preparing hoppers, etc., for sea, wages, and other expenses, £1664: a total of £5218 for the journey both ways. The rent paid was £100 a week for the dredger, and £9 for each of the hoppers. The quantity of material removed during the six months this plant was in use was 336,768 tons. The hiring, fetching, and returning the plant added 3·71*d.* per ton to the cost of dredging the material. Where plant has to be hired, the use of screw hopper dredgers has a great advantage over stationary dredgers, as they can proceed under their own steam to their place of destination.

Dredgers.—The types of dredgers in use may be divided into stationary bucket-ladder dredgers; grab dredgers; pump or suction dredgers, constructed either as stationary or hopper dredgers; eroding and scouring dredgers; rock-breaking dredgers. The stationary bucket dredgers are divided into two classes, having respectively single or double ladders. An advantage is claimed for the latter when the work is large in quantity and the material of a heavy character, and also on account of their being able to dredge close up to a wall. The single ladder has the advantage of being able to discharge into the barges on either side of the vessel by regulating the shoots, whereas with a double ladder each one can only discharge on its own side. Double-ladder dredgers also require more space, and consequently are only adapted for channels where there is plenty of room. Most of the modern dredgers are made with single ladders. These dredgers are made sufficiently powerful to work in the hardest clay packed with boulders, or even in soft rock, in the latter case the buckets being fitted with spikes. The buckets of a first-class dredger will lift stones weighing over two tons, which are taken from them by a derrick crane placed on the dredger.

Bucket-ladder dredgers are constructed, for work in small rivers, about 75 feet long by 17 feet wide and 8 feet deep, and having about 45 I.H.P. engines, and costing about £2500. Such a dredger will raise about 50 tons of clay an hour. The more powerful machines are about 200 feet long by 35 feet beam by 11 feet 6 inches deep; provided with two pairs of engines, each of 250 I.H.P.; each bucket containing 21 cwt., and the whole raising 800 tons an hour. These machines are sometimes made with traversing ladders, so that they can cut their own flotation through shoals.

The last dredger, the *Cairndhu*, built for the Clyde Trustees by Messrs. Fleming and Ferguson, is a good example of the most modern form of machine. It is a self-propelling twin-screw bucket dredger. The dimensions are—200 feet in length, 37 feet beam, 12½ feet deep. There are 47 cast-steel buckets, each of a capacity of 22 cubic feet. She can raise 600 tons an hour of ordinary material from a depth of 40 feet. Traversing-gear for working the bucket-ladder in advance of the hull is provided, so that she can cut her own flotation. The main engines are compound, surface-condensing, indicating 750 I.H.P. There are six sets of auxiliary engines for performing the various operations for manipulating the dredger. A 10-ton steam crane is provided on deck for moving the upper tumbler, etc. The gearing is fitted for two speeds, to suit the different kind of material in which the machine is working. The vessel is fitted with the electric light throughout.

Two twin-screw steel steam hopper barges have also recently been added to the fleet. These are each 200 feet long, 34 feet beam, and 15½ feet deep, and capable of carrying 1000 tons at 10-knot speed and draft of 12½ feet.

Hopper Dredgers are a combination of the ordinary dredger and the steam hopper barge. They are made to carry from 200 to 1200 tons. They are good seagoing vessels, and can steam safely across the sea. The advantage these machines possess over the ordinary dredger is that the first cost of plant is less, no barges being required; they occupy much less space when working, as no barges have to lie alongside, a great advantage when working in a river channel; they can work in exposed situations where it would be impossible for barges to lie alongside a stationary dredger. They can work with a smaller number of men, and the cost of dredging and transport is less than with a stationary dredger and hoppers. An 800-ton hopper dredger requires 13 men in all, and one of 250 tons capacity can be worked with 8 men for the ordinary day shift, these numbers being increased one-half if the dredger is worked night and day. The operation of mooring and unmooring the vessel when at work can be performed in about a quarter of an hour. The cost of a hopper-dredger 115 feet long, 26 feet beam, to carry 250 tons, is about from £10,000 to £12,000.

Grab Dredgers.—These dredgers, originally brought out by Messrs. Priestman & Co., consist of a single opening scoop or

bucket suspended from the end of the jib of a crane by chains specially arranged so as to enable the bucket to be opened and closed. The scoops are made either with smooth cutting edges for soft material, or are provided with steel tines for cutting into hard material or for raising the *débris* of disintegrated rock. The buckets and grabs are made of various sizes, varying in capacity from 5 to 40 cwt. Several modifications of the original design have been brought out, the chief variation consisting in the manipulation of the chain used. They are worked either with a single or double chain, the latter being considered as less complicated in working than those having a single chain. The action of the machine is as follows: On the bucket being released, the chain runs out over the pulley at the jib head, and the bucket descends through the water into the material to be lifted with its cutting edges open, and, the faces or teeth falling perpendicularly. The weight of the grab forces them into the material. The chain is then drawn in by the drum of the winch, closing the grab and raising it.

They are exceedingly useful machines for working in docks or confined spaces, and for harbours and river work where the material is soft. The cost is small, it requires only a small staff to work them, and they occupy a very small space. The size of the machine varies from one capable of lifting from 100 tons to 800 tons a day of soft mud, or 500 tons of more compact material. The price of the smaller machines is about £325, including the engines and boiler, but not the barge; and the largest machines, £875. The cost of lifting soft material to a height of 20 feet with these machines is about 1½*d.* per ton. The smaller machines require a barge about 30 feet long, with 12 feet beam, and the largest 60 feet by 22 feet.

The grab known as the Cockburn dredger is designed with the object of supplying a machine that will excavate material too hard to be operated on by the ordinary form of grab. The scoop is attached to the end of a pole or tube, through which the chains for opening and closing the scoop work; by this means there is no tendency for the jaws to slip up as the scoop is raised. The pole is attached to a movable jib pivoted to the frame of the crane. A depth of 35 feet below water-level can be raised with this form of grab.

Pump or Suction Dredgers.—These machines are principally used for raising sand or mud, the material being pumped up

through suction-tubes, and discharged either into a hopper or through pipes or troughs on to the shore. They can also, by adopting the plan designed by Von Schmidt, of San Francisco, be made to remove clay by having a cutter placed at the end of a shaft working in the suction-tube; the cutter breaks up the material sufficiently small for the detached pieces to be drawn up the suction-tube. When working in heavy sand, the material left in the hopper represents about 50 per cent. of the water and sand raised; in clayey sand, about 40 per cent. remains; and in sticky clay, about 10 per cent.

The advantage of these dredgers is that they can work in any ordinary weather, and at times when it would be quite impossible for dredgers of other types to do so; and the material raised can be delivered directly for distances of from 200 to 300 yards by the force of the pump, so that silt raised from the bed of a river or harbour may be delivered directly at the back of training walls, or used for raising land for harbour purposes. The pumps used will raise and pass through them stones or other hard substances of any size that will pass through the suction-pipes. The cost of the pumps, suction, and delivery pipes, engine and boiler, and everything, exclusive of the boat, may be taken as varying from about £500 to lift 30 tons an hour to £1700 to raise 100 tons an hour.

Suction-hopper dredgers have been used for the removal of the sand constituting the bar of the Mersey, and in the first year's dredging over a million tons were thus removed. Subsequently more powerful machinery was obtained, and a twin-screw suction-hopper dredger was built for the Board by the Naval Construction and Armaments Company at Barrow, capable of carrying 3000 tons of sand, and of raising this quantity in three-quarters of an hour.

For deepening the entrance to the Maas, where the water was so rough that no ladder dredger could have worked, a sand-pump dredger was able to work with waves of three feet running. The vessel was held with one anchor, so as to be quickly slipped. It was 141 feet long, with 27 beam, and hopper capacity of 600 tons. The centrifugal pump had a 6 ft. 3 in. fan running at 120 revolutions a minute, and could raise 230 cubic feet of sand from a depth of 33 feet. Allowing one of sand to seven of water, this left 29 cubic feet of sand as remaining in the hopper. Six per cent. of sand

remained in suspension and went away with the water. It took fifteen minutes to anchor and lower the suction-pipe, and seven minutes to heave the anchor.

In New South Wales, a steam-hopper barge was converted into a sand-pump dredger in 1889, and started deepening the new basin behind Bullock Island in Newcastle harbour. It was calculated that, in making the deep-water channel, about 1¼ million tons of sand were lifted and pumped on land which required reclaiming. Twenty-two acres thus had a commercial value imparted to them of £44,000, the cost of the dredging being £8500. Results as satisfactory followed the conversion of a steam-hopper barge into a sand-pump dredger in Sydney harbour; the silt in this case was pumped a distance of 1100 feet to fill up some low land. Owing to the long distance the material would have had to be wheeled, the cost of conveying by hand-labour would have been 1*s.* 2½*d.* per ton, as against 2¼*d.* with the sand-pump ("Report to Legislative Assembly on Dredging Operations," by C. W. Darley, C.E., 1891).

A new suction dredger, constructed in the colony, 150 feet long by 50 feet wide, with engines of 400 I.H.P. when dredging in clay, has the suction-pipe fixed vertically, and it travels round the end of the vessel. Attached to the suction-pipe is a vertical shaft having horizontal cutters at the bottom. These cutters are hooded over, and as the material is broken up it is drawn into the suction-pipe by the action of the pumps. The suction-pipe is 21 inches in diameter, made in three telescopic lengths, so that a depth of 26 feet can be reached when necessary. The centrifugal pump is capable of raising 16,000 cubic feet of water and sludge a minute. Occasionally bricks, stones, and pieces of iron weighing from 6 to 8 lbs. are drawn up the suction-pipes without injury to the pumps. The cost of this dredger constructed in the colony was £7960. The material as raised is discharged through iron pipes varying from 1000 to 4000 feet in length on to low swampy ground by the side of the channel, which is thus being raised. The method of mooring the dredgers used for these reclamation works is peculiar. Piles fitted with heavy iron shoes are suspended vertically from frames on the deck, the lower end being kept in place by guide-rings. When the vessel is to be moored, the piles are set free, and drop on to and penetrate the ground at the bottom of the channel. When the vessel requires warping

forward, the piles are lifted to their former position by chains passing over winches worked by the engines. The work of raising and depositing this clay and mud on the swamp at the side of the channel was let by contract at prices varying from 1*s.* 1½*d.* to 1*s.* 3*d.* per yard, the contractors finding the plant.

A steam-hopper suction dredger, constructed by Messrs. Simons and Co. for the Natal Government, may be taken as typical of this class of machine. The dimensions of this vessel were, 155 feet long, 30 feet beam, and 12 feet depth. The hull was built of steel, and divided into six water-tight compartments. The deck was of iron, covered with Kauri pine. The hoppers are amidships, and have a capacity of 500 tons; the doors are raised by steam power. The vessel is driven by twin-screws, and has two pairs of surface condensing engines of 500 I.H.P., giving a speed of 9¾ knots. The dredging-plant consists of two 18-inch centrifugal pumps with suction-pipes. The tubes are each 67 feet 6 inches long, and they can dredge sand to a depth of 40 feet from the water-level. The pumps work at 150 revolutions a minute, and absorb 180 I.H.P. At this speed they can raise 1000 tons an hour. This vessel went under her own steam from this country to her destination at Durban without any mishap. A crew of about thirteen hands is required to work the vessel, and the speed when going to and from the discharging ground is about seven knots. The quantity of solid matter deposited in the hoppers varies from 5 to 50 per cent. of the water discharged by the pumps, depending on the description of material operated on. The pumps raise gravel and stones weighing 20 lbs.

In the improvements carried out for deepening the channel leading to the harbour of New York, already referred to, 4,875,079 cubic yards of material were removed under various contracts, at an average cost of 26·4 cents per cubic yard, equal to about 10½*d.* per ton. The material had to be conveyed 10½ miles to sea. The quantity on which the contractor was paid was the quantity in the barges; but this was about 27 per cent. less than the actual quantity removed, the remainder being carried away in suspension by the current. The material had to be raised from a depth varying from 24 to 35 feet under water, the total lift being 36 to 46 feet. In every cubic yard of solid matter thus transported by the barges and paid for, a

large additional quantity had to be raised. The material consisted of mud, clay, and sand, and part of this being nearly of the same specific gravity as the water, when it became incorporated with it, only a certain quantity settled in the barges, the remainder going overboard with the water, and being carried away by the current. The plant provided for doing the principal part of the work consisted of three seagoing dredging steamers, four large barges, and four steam-tugs. These dredgers varied in length from 132 to 157 feet, 31 to 37 feet beam, and 8 to 16 feet in depth, their carrying capacity varying from 275 to 650 cubic yards. Each dredger was provided with two pumping outfits independently arranged. Each pump was capable of lifting 4200 gallons a minute. The suction-pipes, 15 to 18 inches diameter and 60 feet long, were located one on each side of the steamer amidships. To render them flexible so as to accommodate them to the rolling and pitching motion, about 12 feet consisted of rubber supported by chains against the vertical strain caused by the rest of the pipes; the pipes were provided with scrapers at the bottom for loosening the material. The hoppers were divided into compartments surrounded by longitudinal sluice-ways extending either way from a central receiving hopper. These sluices were provided along their course with a series of adjustable bottom and side gates to regulate the discharge of the material into the different compartments, and prevent the listing of the vessels. The steamers worked in all but the roughest weather, and were kept under headway from the time they left their berths in the morning until they returned to it at night. On arriving at the station, the pipes were lowered, and the vessel kept constantly under steering headway until the hoppers were full, when the pipes were hoisted, and the vessel, put under full steam, proceeded to the discharging-ground. Gedney Channel being practically in the Atlantic, the work was exposed to the winds and roughness of the ocean, which occasionally prevented the vessels from working. The time occupied by the largest vessels carrying 650 cubic yards was thus distributed: pumping, 48·6 min.; transporting, 1 hr. 11 min.; under steam per day, 16 hrs. 4 min.; loads per day, 6·73; cubic yards, 3936·65; time lost by repairs, 2 hrs. 24 min.; lost by weather, 32 hrs. 50 min.

The *Thyboron*, constructed by Messrs. Lobnitz and Co. for the Danish Government, is 165 feet long, 34 feet beam, and

12 feet deep. Her draught, light, is 6 feet 6 inches, and loaded to her full capacity of 700 tons, 10 feet. There are two pumps, capable of discharging 2400 cubic feet of water only per minute when working at their normal speed, which can fill the hopper with 600 tons of sand in half an hour on a coal consumption of 2½ cwt.

Combined Dredgers.—Dredgers are frequently made so as to be adapted to several different kinds of work. Thus a steel screw self-propelling combined sand-pump and bucket-hopper dredger, called the *Veracouz*, was constructed by Messrs. Fleming and Ferguson for harbour work in Mexico. Her dimensions are 150 feet long, 30 feet beam, and 12½ feet deep. She is capable of raising 300 tons an hour from a depth of 35 feet, and of carrying 300 tons. She is fitted with the ordinary bucket ladder fitted with teeth for rock-cutting, and also centrifugal pumping machinery for raising sand and discharging it through floating pipes a distance of a quarter of a mile. The engines are of 300 I.H.P. She steamed to Mexico under her own steam.

A steel twin-screw hopper dredger, recently constructed by Messrs. Simons and Co., of Renfrew, for the Russian Government, has a hopper capacity of 1000 tons, and the buckets can raise the same quantity of free soil in an hour. It is provided with two sets of buckets, the larger containing 25 cubic feet, and the smaller, for dealing with hard material, 11 cubic feet. Steel ripping picks for disintegrating hard material can be substituted for every second or third bucket. It is also provided with a centrifugal suction-pump, which can raise 500 tons of sand an hour. The dredger works to a depth of 36 feet of water. The engines are compound surface condensing of 1000 I.H.P. collectively, each driving its own propeller. Steam is supplied at a pressure of 100 lbs. Steam winches are fixed at the bow and stern for handling the mooring-chains. The hopper doors are also worked by steam power. Two steam cranes control the movement of the bucket ladder and suction-pipe. The ladder is hoisted by twelve steel ropes, the lifting barrel being worked by steam. The vessel is lighted throughout by electricity.

Shore-delivery Dredgers and Transporters.—When it is practicable to deliver material raised by bucket dredgers on to the shore or sides of the channel, this is accomplished either by

dredgers having long ladders and discharging directly at a great elevation into pipes or troughs, the travel of the material being assisted by a stream of water forced along the pipes by a centrifugal pump; or the material is raised from the barges and discharged in the same manner. These dredgers are made with the tumblers as much as 80 feet above the water-level, and, where required, can cut their own flotation, and deliver the spoil over high banks on to the shore. When the material is not suitable for conveyance along pipes or troughs, it is conveyed to the shore by a travelling platform moved by an endless chain. Shore-delivery dredgers have been extensively used in the Seine at Rouen, in the Gironde, and on the Weser.

During the construction of the Suez Canal, M. Lavally employed suction dredgers, and sent the material through shoots 230 feet long. Sand flowed through these shoots, with a sufficient quantity of water, at an inclination of 1 in 20. Sand mixed with shells would not travel at an inclination of 1 in 10, and an endless chain had to be used. Stiff clay fell in lumps, but worked along the shoots which were provided with the endless chain.

In the dredging operations carried on for improving the navigation of the Garonne between Bordeaux and the sea, three bucket dredgers and two cutting suction dredgers were employed. The bucket dredgers were of 120 H.P., and discharged their material by means of a distributor and centrifugal pump through floating iron tubes 12 inches diameter with leather joints. Each machine conveyed about 11,000 cubic yards a month to a distance of 1000 feet, at a height of about 15 feet. The material was a sticky clay, and its progress was assisted along the tubes by an auxiliary pump placed on a barge alongside the dredgers. Of the two cutting suction dredgers, one had a suction-pipe 12 inches in diameter hung at the side of the dredger, the position being regulated by chains and pulleys. A set of cutters moved by gearing from the dredger, was fixed on an axle placed at the end of the frame carrying the pipe, and beyond its mouth, so that the cutters drew the material they detached towards the pipe. With 40 H.P. this dredger discharged 11,000 cubic yards of material in a month through floating tubes to a distance of 1000 feet, at an elevation of 16½ feet. The suction-pipe of the other dredger was 15 inches in diameter, and was placed in a central well of the barge, and entered a central longitudinal recess when raised

horizontally. The cutting discs revolved at the rate of fifty revolutions a minute. This dredger has engine-power of 129 H.P., and can remove 39,000 cubic yards a month from a depth of 25 feet below the water-line. These dredgers are worked by four men, whereas the bucket dredgers require seventeen men. The average proportion of solid matter raised by the suction dredgers when working in sticky clay is 10 to 12 per cent. of the watery mixture raised, but it reaches 40 per cent. in clayey sand.

Another machine used in the Garonne works consisted of an excavator running on rails, the buckets scooping away the river-bank, where it had to be removed, to a slope of 1 to 1. The material was delivered from the buckets on to an endless band 4 feet wide, carried on rollers placed 3·28 feet apart. This band traversed a gantry consisting of two wrought-iron girders, divided in spans of 131 feet, supported on wrought-iron piers running on rails. The band was worked by an engine placed on rails between the excavator and the staging, which, by a wire-rope transmission running the whole length of the staging, and of a spur-wheel and worm gear fitted on each pier, worked the endless band and pulled the staging and itself along at the same speed as the excavator was doing the work. The material was carried by the endless band 1140 feet. The length of rails under each pier was 984 feet.

During the construction of the Manchester Ship Canal, a soil-transporter, designed by Mr. John Price, was used for conveying the material from the cutting to trucks on the bank. The material removed was mud, sand, and clay. The transporter consisted of a trussed wooden box girder 94 feet long, 5 feet wide, and 6 feet 6 inches deep, supported at its extremities by two decked barges 70 feet long, 14 feet beam. This girder carried a set of steel shafts and flanged rollers, over which travelled a band of a total length of 330 feet, made of elm, 4 feet wide and 8½ inches deep, bolted to two endless chains 3 inches deep, 1 inch wide, and 2 feet pitch. The points of the band were covered with thin iron plates, to prevent spilling and lessen the wear on the edges of the boards. The girder on the boat nearest the shore was hinged so as to be capable of being raised or lowered, and was supported from a jib by chains. The band passed round hexagonal tumblers at either end of the girder. The material was delivered from the dredger direct on to the band at any part of its length between the boats, and, travelling along the

girder, was delivered into the trucks on the shore by means of the projecting girder supported by the jib. The chain of the endless band travelled on flanged steel rollers 7 inches in diameter, keyed on to steel spindles $1\frac{7}{8}$ diameter. It was driven by a 10 H.P. engine, having a vertical boiler, the engine running at 120 revolutions a minute to $5\frac{1}{2}$ of the driving tumbler, the band travelling at the rate of 66 feet per minute. A full description of this machine, with illustrations, will be found in *Engineering* of July 24, 1891.

On the North Sea and Baltic Canal, shore deliverers, consisting of two vessels connected together by cross-girders, were used, a sufficient width being left between the vessels to form a well large enough for a barge to float into. The dredged material is raised out of the barges by a double set of ladders and buckets to a height of 34 feet 5 inches above the water-line into troughs 164 feet long, running to the shore, the material being carried along by a strong stream of water supplied by a centrifugal pump. One vessel is provided with a compound engine of 150 H.P. for driving the two pumps. In the other vessel is a compound engine of 100 I.H.P. for working the buckets. The vessels are 82 feet long, 14 feet 9 inches beam, 6 feet 7 inches deep; average draught, 4 feet 7 inches; space between the two vessels, 21 feet 6 inches. The buckets have a capacity of 5·65 cubic feet, and the speed of the travel is at the rate of 25 to 30 buckets a minute, so that, with both ladders working, 50 to 60 buckets are discharged a minute. The gradient of the shoots is 1 in 25. About 350 cubic metres of material is elevated an hour. The troughs are supported by a derrick fixed on the vessel.

In the construction of the Mexico Drainage Canal in 1892, five Couloir dredgers, constructed by Messrs. Lobnitz and Co. of Renfrew, were employed. These were capable of dredging to a depth of 56 feet below the water, and of cutting a face in front 9 feet above water-level. The material was lifted by buckets to the top of a stage on the dredger, and thence conveyed to the shore on either side of the canal along troughs supported by derricks fixed on both sides of the vessel.

Rock-dredgers.—Formerly, where rock had to be removed, the material was first broken up by blasting, the pieces being afterwards removed by buckets or grab dredgers. More recently, where the rock is soft or easily acted on, this has been removed by means of strong steel claws, either fastened on to the buckets

of a powerful dredger, or every alternate bucket is replaced by the claws.

Where the rock is too hard to be acted on by this means, it has been broken up by the use of heavy rams. The rock-cutters have the form of heavy chisel-pointed rams, which, after being raised, are allowed to drop from 10 to 20 feet on the rock. With rams of sufficient weight the hardest rocks can thus be broken up, the *débris* being removed by grabs. For small works a single cutter is sufficient, and the removal by this means can be effected at very much less cost than by blasting.

For the removal of submerged rock, a machine (shown in Fig. 34) has been designed by Mr. Lobnitz, termed a "Dero-

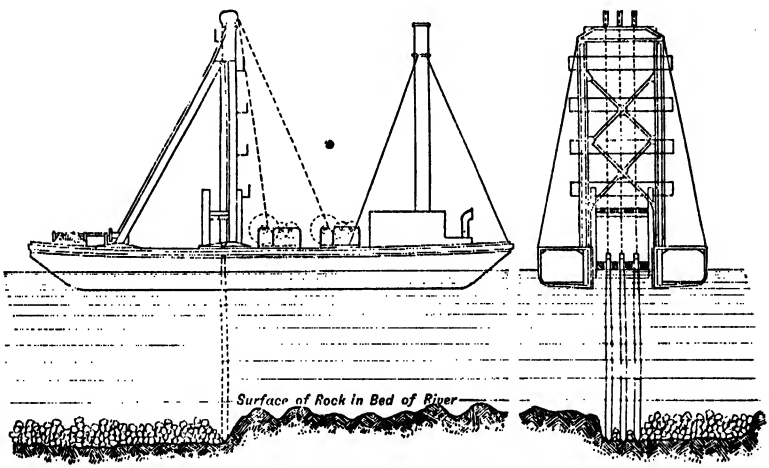


FIG. 34.—The Lobnitz rock-breaking dredger.

cheuse." By the aid of this dredger the rock is broken up into pieces sufficiently small to be removed by a grab or buckets.

Several of these machines were supplied by Messrs. Lobnitz and Co. of Renfrew for removing a shoal containing about three million tons of hard limestone rock, in the Suez Canal. The first dredger constructed was 180 feet long, 40 feet broad, and 12 feet deep. It was fitted with ten heavy chisel-pointed rams, or rock-cutters, each 42 feet long, and weighing 4 tons. Five of these were fitted on each side of the well, through which the broken rock was lifted by a ladder and buckets, the bag of the bucket-chain being supported by a guide-wheel specially designed by the makers to relieve the strain on the bearings, bucket-links, and pins. These rams were raised by hydraulic power, and allowed to fall from

10 to 20 feet on the rock, and deliver from 200 to 300 blows an hour. The bucket-chains were driven by a four-cylinder compound engine of 200 I.H.P. When at work the machine was moved over the surface in a series of arcs by winch motion, arranged by swinging the vessel from side to side, pivoting on a steel mooring pile 3 feet in diameter, which passed down through the hull in the after part of the vessel and rested on the rock. There were two of these piles manœuvred by hydraulic power enabling the vessel to advance a given distance after each swing, and preventing her losing her position. The cost of cutting and dredging the rock was stated by Mr. Lobnitz to be 2*s.* 8*d.* per cubic yard, or, including all expenses except transport, 5*s.* per cubic yard. A full description of the machine used in the Suez Canal will be found in the *Proc. Inst. C.E.*, vol. xcvii.

A machine constructed on this principle was also used for the removal of a hard reef of rocks at Pernambuco, situated about 36 feet below the surface. The cutters were 40 feet long, and weighed 8 tons each. They were actuated by a crane used for depositing concrete blocks. The broken rock, reduced by the chisel-pointed rams to the size of ordinary ballast, was raised by a 30-cwt. grab working 35 feet below the surface.

These dredgers have also been in use breaking up and removing the rock at the "Iron Gates" of the Danube. The barges on which the rock-breaking apparatus for the Danube was fixed were 80 feet long, 25 feet wide, by 7 feet deep, and the cutter reached to a depth of 36 feet below the water-line. The cutter was 40 feet long, and weighed 8 tons.

One of these rock-cutters was also used in excavating the Government dock at Malta. This machine was supported by a strong girder resting on two hopper barges, and worked by two semi-portable engines; three 8-ton cutters were employed. The machine constructed for the New South Wales Government was worked from a vessel 100 feet long, 35 feet beam, and 8 feet deep. Three 8-ton cutters, 39 feet long, were driven through a well amidships, the engine being placed forward; this vessel was manœuvred by winches.

For small works a single cutter can be used, and this may be mounted on any barge of sufficient size. These smaller cutters weigh 6 tons, and are driven at the rate of 35 blows an hour. They break the rock into pieces of an average size of 2 cubic feet per blow, and can work in any tideway, and up to 40 feet below the surface.

The engine-power required to work a single cutter is about 60 I.H.P., and the cost of the cutter ready for fixing on the barge, including winches and derrick and spare gear, but exclusive of the barge, is about £2000.

One of these smaller rock-dredgers has been built for Limerick harbour.

The advantage claimed by these rock-cutters is that the rock broken by them can be lifted at a small cost. The cost of breaking the rock is not less than by explosives, but the broken pieces, being smaller, are more readily lifted by a grab.

Another form of rock-breaking machinery used on the Danube rocks consisted of steam hammers carrying cross-cut chisels $9\frac{7}{8}$ inches in diameter, and delivering 100 to 150 blows a minute. These hammers worked under a pressure of 73·5 lbs. per square inch in elliptical caissons 7 feet 3 inches diameter on the major axis, suspended on framing between guides, and placed 6 feet 10 inches apart centre to centre on the barge. The caissons were raised or lowered by hydraulic power to a maximum depth of 13 feet below the surface of the water. The effective work of the chisel was reckoned at 21,690 foot-pounds. The whole surface of the rock by this means was completely disintegrated, the current removing the *débris* without the necessity of dredging it up. Six of the hammers were fixed on a vessel 115 feet long, 21 feet 4 inches beam, and 8 feet 3 inches deep. The cost of breaking up the rock by this means was 9*s.* 7*d.* per cubic yard.

Eroding Dredgers.—Various attempts have been made from time to time to disturb and break up shoals in rivers by mechanical agency. Harrows of different descriptions have frequently been used for this purpose, and the first attempt at deepening the river Clyde was accomplished by the use of both harrows and ploughs.

On the Danube a boat fitted with a triangular rake hung over the bow of a steamer was dragged across the shallows, the steamer running astern. By this the shoals, which consisted principally of shingle, were removed, and the depth of water increased from 3 feet to 4 feet.

Harrows have also been used for removing the shoals at the lower end of the Volga. The harrows were towed over the shoals at the rate of about 7 miles an hour by a steam-tug, and the depth increased by this means from 2 feet 4 inches to

6 feet 5 inches. The chief advantage which the harrows conferred was in loosening and disintegrating the crust found on the top of the shoals, after which the current was able to transport the material away.

Another means of erosion used is by fixing movable dams across the channel to be operated on. This plan was tried in the river Stour, which is about 50 feet wide and 6 feet deep. At the beginning of the present century, a boat was fitted up for the purpose of removing shoals in this river. A machine of this description is still used for clearing out the mud which accumulates in the river between Sandwich and the sea, a distance of 12 miles. One or more barges are fitted with a central and two wing dams, the whole covering the entire width of the channel. These dams are attached to frames, and are raised and lowered by chains actuated by winches on the deck. Where the ground is hard, they are fitted with spikes or scrapers on the bottom. When the dam is lowered, a head of from 6 to 12 inches accumulates at the stern, and this is sufficient to drive the boat slowly forward, and the mud and silt, being loosened by the cutter, is scoured out and carried away by the current. The boat never attains a greater speed than 3 miles an hour, and it takes from 5 to 6 days to clean out 5 miles of the river.

In the Garonne a somewhat similar contrivance was used for deepening the river.

The Kingston floating scouring dam, constructed on a similar principle, has also been used in scouring out the tidal outfalls of the drains emptying into the river Welland, and the entrances to the tidal and coast canals at Balasore and other places in India.

Another eroding process is that of forcing air or water amongst the sand or mud to be removed, and even clay may be operated on in this manner by directing a powerful jet of water on to it. At a trial recently made at the mouth of the river Arun, near Littlehampton, it was stated that very successful results were obtained, and even stiff clay removed to a depth of 5 feet, by means of a jet of water driven through a 4-inch flexible pipe having a $1\frac{1}{2}$-inch nozzle, the water being forced through the pipe by a pair of horizontal direct-acting $7\frac{1}{2}$-inch pumps, having a 14-inch steam cylinder, with steam pressure in the boiler of 60 lbs. The apparatus was fixed in a tug.

The removal of deposit from a reservoir in Algeria was effected by forcing air through a pipe into the sediment by a 12-H.P. engine, and thus mixing the deposit, which had accumulated to a depth, at the lower end, of 24 feet, with the water, and allowing it to run off down the bye-pass. As the mud lowered near the dam, that from the upper part flowed down. The water became muddy for a distance of 110 feet round the pipe.

The screws of steamers have also been used successfully for eroding and disturbing material.

Revolving cylinders, with spikes suspended from frames at the bow and stern of a barge, have been used. The cylinder, termed "a hedgehog," is allowed to rest on the bottom of the channel, and, as the boat is drawn along either by horses or by a wire rope coiling on a drum driven by an engine on the boat, it revolves, the spikes eroding and churning up the bottom, and tearing up the weeds. A machine of this description has been successfully used in deepening the tidal river Welland. The material disturbed in this case consisted of alluvial deposit, and had to be carried in suspension 14 miles before it reached the estuary. The velocity of the current varied from $2\frac{1}{4}$ to 3 feet a second, and no deposit in the channel occurred.

For the deepening of the Upper Mississippi, Ohio, and other rivers in America, it was determined some years ago to effect this by digging or stirring up the material so that the current might work the shoals into the deeper places. Numerous schemes were submitted to the commission appointed by the Government, of which the following is a brief description: A steamboat with two large screws fixed obliquely on each side of the bow; these, when working, were to draw the boat along through the water and throw the material on each side. A steamboat with two endless screws placed on an horizontal axis at the end of the boat, and so arranged as to lower into the shoal places. A modification of this plan was also proposed by substituting saw teeth in the shaft instead of the screws. A wheel placed between twin boats and turned by the action of the stream, the boats being moored; a temporary wing dam was to be fixed above the wheel to increase the action of the current; small ploughs or harrow teeth were to be fixed on the arms of the wheel, which was made adjustable to the depth. A boat, with double-acting steam-pumps, which were to force

water through a set of 28 nozzles, 3-inch diameter, on to the shoals. A drum attached to the stern of a steamer in lieu of the ordinary stern wheel; the drum was to have scrapers attached to the convex side in spiral lines leading outwards. Four scrapers made of boiler plate fastened in a triangular frame, suspended from the stern of a steamer; the frame had a 16-feet base, and weighed altogether $2\frac{3}{4}$ tons, and the scrapers were something in the form of the buckets of a dredger; two engines were required to work this machine, which had cylinders 20 inches diameter, with 7-feet stroke. This machine was the one selected by the commission, and was set to work on the upper part of the Mississippi, on the Ohio and Missouri. By its use the former river between St. Paul to La Crosse was deepened from 2 feet to 4 feet.

In the Columbia river in America, to remove the shoals which impeded the navigation, the screw of a propeller of a large ocean steamer was used, which generated a current sufficiently strong to erode a channel. By this means, a channel 1200 feet long, 2 feet wide, and 6 feet deep, was cut in 3 days; and on a subsequent occasion, a channel 1600 feet long, 150 feet wide, by 10 feet deep, in 8 days. The material moved was heavy sand. The method of working was by backing the steamer to the shoal, and mooring her by the bow to an anchor up stream and to anchors on each quarter. The vessel being trimmed by the stern just to clear the bed of the river, the engines were started full speed a-head. The generated current, being driven away from the ship, carried the material with it. As the cut proceeded, the vessel was slewed from side to side by her rudder, and as soon as a trench was cut across the full width of the channel she was floated down about 25 feet into position for a fresh cut. It was estimated that the stream immediately astern of the ship had a velocity of from 12 to 14 miles an hour; at a quarter of a mile aft, a speed of 3 to 5 miles. The stream carried the bulk of the eroded material across the bar into deep water, while a small portion was thrown up as a bank on the side of the channel towards which the propeller turned. The bottom of the eroded channel was seven feet below the propeller, and it was proved that an ordinary steamer could by this means sluice out a channel deeper than her own draught requires.

During the construction of the new channel of the river from Rotterdam to the sea, a boat was used fitted on each side with

a screw propeller, 3 feet 6 inches in diameter, which could be raised or lowered by gearing on the deck. The screws were adjusted so as nearly to touch the shoals, and as the boat moved these were caused to revolve at the rate of 150 revolutions per minute. By the aid of this machine shoals of sand were moved at the rate of 130 cubic yards an hour, and clay mixed with sand at the rate of 116 cubic yards. The machine was afterwards converted into a suction dredger, having a centrifugal pump with a two-bladed fan, 4 feet 6 inches in diameter, by which sand was pumped up and discharged into the river on the ebb tide.

At Tilbury Docks the tide from the Thames enters the tidal basin through the piers at the entrance with considerable velocity, bringing with it a large quantity of mud in suspension, which is deposited in the slack water. To remove this, four large dredgers were formerly used, the weekly cost amounting to about £1000. Subsequently this deposit has been removed by the use of a steam-tug, provided with pumps attached to an iron tube trailing in the mud on the bottom of the basin by indiarubber pipes. Water is forced through the tube into the mud, which is thus stirred up and kept in suspension, and flows out with the ebb tide. The weekly cost has by this means been reduced to £27. A full description of this apparatus will be found in *The Engineer* of August 16, 1889.

The same process was tried at Swansea for the purpose of keeping the entrance up to the docks clear from deposit, but in this case the material to be removed consisted of silt and sand, which did not remain in suspension long enough for the current to carry it away to a sufficient distance.

The most complete machine used for deepening channels by erosion is Wheeler's Eroder Dredger. The eroder consists of a cone-shaped cutter 4 feet in diameter at its widest part, having a number of blades fixed on the periphery. This cutter is fixed on a steel shaft working in a frame, which can be raised or lowered through a well in the boat, and is driven at a speed of a hundred revolutions a minute.

An Eroder Dredger, built of steel, for the Boston Harbour Commissioners, by Messrs. Scott and Co. of Goole, under the author's directions, was 46 feet long, 13 feet beam, and 6 feet deep. It was provided with a well forward, in which the frame carrying the shaft of the cutter worked. The cutter was driven

by a pair of compound engines of 35 I.H.P., these engines also being used for raising and lowering the frame, working the winches, and also the screw for propelling the boat. A 5-cwt. Priestman grab was fitted on the deck for use when the eroder was not working; this was worked by an independent engine. The cost of this machine complete was £1450. An Eroder Dredger of similar construction, but without the grab, built for the author by the same firm, cost £1060. These machines are capable of eroding and disturbing either warp or hard clay. The cutter, revolving rapidly, disintegrates the material to be acted on, and the rapid revolution of the blades causes a strong centrifugal current in the vicinity. The peculiar form given to the cutter allows it, as the boat is warped forward, to keep cutting away the material and detaching small pieces, which are whirled round and rubbed against the face. The detached material is thus so rubbed together and churned that the particles become completely disintegrated and reduced to a size sufficiently fine to float and be carried away by the current in suspension. The machine thus automatically adjusts the size of the particles to the strength of the current. Shoals of soft material can be removed by this machine at a total cost of less than a penny a cubic yard, and of hard material at a cost varying from this to twopence, according to the compactness of the material. The efficiency of the machine depends to a great extent on the form of the cutter.

Cost of Dredging.—The following examples of dredging have been selected as ranging over a wide number of typical cases. From these it will be seen that material raised and transported by hopper dredgers costs less than when raised by stationary machines, and that suction dredgers afford the most economical means of raising material.

The Clyde.—About a million and a half cubic yards are dredged annually out of this river, at a cost, for 1890, of £38,667. or about 6·06*d.* per cubic yard, or say 4·60*d.* per ton, of which £13,954 was for maintenance of the channel at its normal depth, and £24,713 on account of improvements.

Between 1845 and 1890, 35,205,242 cubic yards were dredged. The plant used by the Trust consists of two double-ladder dredgers, capable of dredging to 28½ and 32 feet; three single dredgers, capable of dredging to 33 feet; a floating steam digger, fitted with 10-ton crane; eighteen steam hopper barges, besides

a number of other boats and appliances. Recently there has been added to the fleet a new bucket single-ladder dredger of 750 I.H.P., capable of raising 600 tons an hour from a depth of 40 feet, and two large steam hopper barges.

The average cost of dredging sand, mud, and clay from Port Glasgow and Bowling harbour and conveying it 27 miles to Loch Long in 1871–72, as given by Mr. Deas in his paper (*Min. Proc.* I.C.E., vol. xxxvi.), was for—

	Pence per cubic yard.	Equal to per ton.
Dredging	2·45	1·86
Conveying	4·28	3·25
Total ...	6·73	5·11

For hard till and clay from Erskine Ferry, North Bar, and Elderslie Rock, and conveying to the same place—

	Pence per cubic yard.	Equal to per ton.
Dredging	13·88	10·54
Conveying	13·82	10·50
Total ...	27·70	21·04

In the year 1892, the total quantity dredged amounted to 1,598,984 cubic yards. Of this, 651,648 cubic yards were taken from the excavations for the Cessnock Docks. One of the dredgers raised 646,080 cubic yards, the engines working 3417¼ hours, equal to 189 cubic yards per hour.

For dredging in the lower part of the Clyde at Greenock, Mr. Stevenson gives the cost of dredging and conveying soft material 7 miles to Loch Long as—

	Pence per cubic yard.	Equal to per ton.
Dredging	2·54	2·06
Conveying	2·47	2·00
Total ...	5·01	4·06

The work was done with a single-bucket ladder, capable of lifting 500 tons an hour, and three screw hoppers.

For removing a patch of stiff clay and boulders at Garvel Point the cost was 18·03*d.*

In 1892 the quantity dredged was 188,875 tons, the quantity in the previous year being 478,000 tons. The recent dredging has been amongst a bed of hard clay and boulders near Port

Glasgow, some of the stones weighing from 5 to 6 tons. Altogether in one year 155 of these large stones were raised, weighing altogether 981 tons.

The Tyne.—The quantity of material removed out of this river between 1838 and 1890 was 87 million tons. In one year the quantity dredged was 3,591,947 tons. The average cost of dredging and conveying this to sea in hoppers was 1·85*d.* for dredging, and 1·54*d.* for transport; a total of 3·39*d.*, including repairs, but not interest on outlay or depreciation. For stiff clay and boulders the cost was 6·34*d.*, and sand 2·35*d.*, conveyed 6 miles. Mr. Messent estimates that repairs cost $\frac{6}{12}$, coals $\frac{1}{12}$, wages, stores, etc., $\frac{5}{12}$, of the total cost. Where rock had to be blasted, the prices were—

	Pence per ton.
Blasting	1·60
Dredging	6·21
Conveying	3·60
Total ...	11·41

The above prices include repairs, but not interest or depreciation.

In 1889, 2,090,814 tons of material were removed at a cost of 3·59*d.* per ton. The cost was divided as follows:—

	Dredgers.	Hopper barges.	Total.
Wages	28 %	48	38
Coal and coaling ...	9	12	11
Repairs	54	37	45
Stores	4	3	3
Watching	5	—	3
Total ...	100	100	100

The plant consists of 5 double-ladder dredgers, dredging from 29 to 36 feet; 1 single-ladder dredger; 8 steam-tugs; 47 wooden hopper barges; 10 screw steam hoppers. From 1858 to 1890 £300,000 was spent in dredging-plant, and £1,557,036 on dredging.

The Tees.—Between 1854 and 1889, 24½ millions of tons were removed, and upwards of £400,000 was expended in dredging and the necessary plant. In 1889, 1,003,130 tons were dredged, at a cost of £18,812, equal to about 4·50*d.* per ton. The plant consists of 4 double-ladder dredgers; a Priestman grab; 8 steam-tugs; 35 hopper barges, and other appliances, the total value being estimated at £114,000.

In a paper in the *Proceedings of the Institution of Civil*

Engineers, Mr. Fowler gave the cost of dredging 18,557,820 tons up to the end of 1885 as £387,536, of which £138,036 was for plant, and £249,500 for dredging and conveying to sea. The particulars of working two of the dredgers in removing 1,368,000 tons are as follows :—

		d.
Wages, stores, and maintenance	... ...	1·670
Coal	... ...	0·120
Repairs	... ...	0·614
	Total ...	2·404

The material removed was principally sand, which was transported to the sea.

The cost of blasting, dredging, and removing 124,000 cubic yards of oolite rock was £26,781, equal to 4·32*s.* a cubic yard. This same rock has since been removed by the dredger by means of steel claws fixed on the bucket-chain.

Hartlepool.—4,635,845 tons have been removed during 21 years up to 1891, or about 270,000 tons a year. The average cost of lifting and transporting has been 2·773*d.* per ton. In 1891, 200,660 tons were dredged at a cost of £2605, or 3·11*d.* per ton, the average cost for 1890 being 3·386*d.* In 1892 the average cost was 7*d.* per ton.

Belfast Lough.—For cutting a deep-sea channel through the sand and clay-banks for the navigation of the outfall of the river Lurgan, two twin-screw hopper dredgers, having engines of 1000 I.H.P., of a capacity of 800 tons, were employed, each capable of lifting 500 tons an hour, and of working to a depth of 30 feet. The dredgers commenced work in 1885, and during the greater part of the time worked night and day by the aid of the electric light. The distance of transport was 10 miles. The quantity raised and carried to sea was 5,474,424 tons. The average cost for wages, coal, stores, and repairs is given as 2·17*d.* per ton, the interest and depreciation being estimated at 1·25*d.* The total time of working was 55½ months; the average weekly tonnage dredged and deposited by each machine was 12,330 tons. About one ton of coal was used in the removal of 404 tons of clay and sand. The ordinary number of engine-hours run a day was 21½, but the average for the 6 days, 19¾ hours. Four journeys were made in a day, the dredging occupying 1½ hour and the transport 3¼ hours. Some of the material dredged out of the river channel has been deposited on to the

slob lands at the side from scows by hand-labour, and this cost 1*s.* 11*d.* per ton. It is, however, now intended to deposit this material in a much more economical manner.

Blyth.—A hopper dredger of 800 tons capacity, working at Blyth, raised in 531 hours 153,243 tons. The steaming-time was 210½ hours, the material being conveyed two miles to sea. The cost per ton is given by Mr. Sandeman as 1·03*d.* per ton for wages and stores, but exclusive of hire and repairs.

Carlingford Lough.—In dredging the bar away here, the operations were considerably delayed owing to the roughness of the sea. Dredging could seldom be carried on when the wind blew from the southern half of the compass. In 1871 the dredger was only able to work on 67 days, and in 1873 on 131 days, and on many of these days only for from two to three hours. The material removed was plastic blue clay, with shingle and boulders up to 4 tons weight. The rise of tide in the Lough was about 16 feet, and the new channel was excavated so as to give 18 feet at low water. The dredgers were twin-screw, with engines of 60 N.H.P., capable of raising 150 tons an hour. There was one steam hopper barge of 180 tons, and two hoppers without steam, and a tug. The dredger was so constructed as to be able to lie at anchor on the bar in rough weather. The average amount raised in one day's work was 850 tons. The cost, including insurance, was 1*s.* 5*d.* per ton, of which $\frac{6}{10}$ was for dredging, and $\frac{4}{10}$ transport. It took one ton of coal to 120 tons of material. The lowest contract that could be obtained for this work was 3*s.* per ton.

Aberdeen.—The cost of dredging, and discharging one mile from the pier-heads, three million tons of clay, boulders, gravel, and sand during the years 1867–80 is given by Mr. Smith as averaging 5·85*d.* per ton, including wages, coal, stores, and repairs. Interest is estimated at 1·50*d.* Assuming one ton to equal 18 feet of solid ground or of excavation, this is equal to 11¼*d.* per cubic yard, measured *in situ.* The quantity of stones lifted amounted to 17,000 tons. Four single-ladder bucket dredgers are in use, and eight hopper barges. In 1892, 206,270 tons of silt were raised, at a cost of 5*d.* per ton, and 624 tons of boulders at 8*s.* 5*d.* per ton.

Ayr.—With a hopper dredger having a capacity of 500 tons, the cost per ton of dredging and conveying 3 miles 78,194 tons of material, consisting of four-fifths clay and boulders, one-fifth

sand and silt, was 0·940*d.* per ton, exclusive of repairs. Wages were 0·703*d.*; coal, 0·147*d.*; stores and oil, 0·090. The vessel required ten hands to work her. The time occupied in the work was—

Transport	73·47
Repairs, etc.	4·02
Coaling	2·68
Detention from weather	10·39
Other detentions	9·44
Total ...	100·00

The cost of dredging the same material by a stationary dredger was 4·897*d.* per ton.

Wick.—The removal 130,000 cubic yards of clay and boulders from Wick harbour cost £17,355, or at the rate of 2*s.* 9*d.* per cubic yard.

Swansea.—The cost given by Mr. Capper of dredging a new channel from the estuary to Swansea Dock, the material consisting of mud, clay, and gravel, was for 336,768 tons, removed with a dredger and hopper hired from the Tyne Commissioners—

	Pence per ton.
Cost of bringing and returning dredger and hopper ...	3·71
Hire of plant	3·20
Working	1·93
Towing	0·93
Repairs	0·68
Total ...	10·45

Subsequently, with a double-ladder dredger capable of lifting 900 tons an hour, purchased at a cost of £27,500, with hoppers costing £2100 each, the dredging and conveying cost 3·525*d.* per ton, exclusive of interest or depreciation. The percentage of time occupied in the work was—

Repairs	16·36
Coaling and delays from traffic, etc.	17·36
Bad weather	16·50
Dredging	49·78
Total ...	100·00

Boston Haven.—The bed of the river Witham, which passes through the harbour of Boston, consists of hard boulder clay, overlaid in places by softer brick clay. The lowest tender which could be obtained for deepening the bed of this channel 3 feet over a distance of about 3 miles, was 2*s.* 6*d.* per cubic yard

measured *in situ*, equal to about 1*s.* 8*d.* per ton. In this case the contractor had to bring the dredger to the river from a distance, and the quantity to be removed was comparatively small. The distance the material had to be conveyed to the estuary was 6 miles. Subsequently the same channel was deepened from 1 foot 6 inches to 2 feet by an Eroder Dredger, at a cost varying from 1·26*d.* to 2·97*d.* per ton, according to the hardness of the material, the current itself transporting the material away. By the same means, shoals of alluvial matter, which had accumulated in the river and at the approach to Boston Dock, were removed at a cost of from 0·75*d.* to 0·94*d.* per ton, the price previously paid for the work done by contract being 1*s.* 6*d.* per ton. In a report presented to the commissioners it was shown that the saving in two years on removing 37,434 tons of material from the shoals and from the bed of the river, as compared with the cost of removal at the previous contract prices, had been £2370, the average cost, including hard clay and alluvial matter, being 2·38*d.* per ton, the total outlay on the machine, including a Priestman grab, having been £1547.

Lowestoft.—The dredger used by Mr. Langley here was 60 feet long by 20 feet beam. The suction-pipe was 12 inches diameter and 25 feet long, made of indiarubber, strengthened by coiled wire inside. A derrick supported the flexible tube, and raised and lowered it. The pump, the fan of which was 2 feet in diameter, raised on an average 200 tons of sand, gravel, and stones per hour, working in a depth of 25 feet, the maximum quantity being 400 tons. Occasionally large stones and iron bucket-pins over 3 lbs. in weight were sucked up. The cost of the dredger was £2000; and of raising the material and conveying 2 miles to sea 2*d.* per ton, the quantity raised being about 200,000 tons a year.

The Mersey.—A hopper dredger, employed under the direction of Mr. G. F. Lyster for the Mersey Docks and Harbour Board, fitted with four grab buckets, and having hopper capacity of 900 tons, raised from the docks and delivered the material 8 miles to sea at a cost of 1·78*d.* per ton, of which 0·81*d.* was for wages, 0·31*d.* for coal and stores, 0·66*d.* for repairs. For deepening the bar of the Mersey, two steam hopper suction-dredgers of 500 tons capacity, fitted with centrifugal pump and suction-pipes, have been used. Up to the spring of 1892, 860,000 tons of sand had been removed by this means. The dredgers removed on an average each 300 tons an hour, in-

cluding the time occupied in transport. The experiment having proved thoroughly successful, the Board have had built for them, by the Barrow Naval Construction Company, a twin-screw hopper suction-dredger capable of holding 3000 tons. The length is 320 feet; beam, 46 feet 10 inches; depth, 20 feet 6 inches. The vessel is divided in eight hoppers, a well being formed in the middle for the working of the suction-tubes, which are 3 feet 6 inches in diameter, and can be lowered to a depth of 45 feet. There are two centrifugal pumps 3 feet in diameter, capable of raising 4000 tons an hour, driven by two sets of triple expansion engines. The engines are capable of filling the hoppers and taking the vessel to the place of deposit and back again in an hour.

Queensland.—In an official report of the Engineers of the Harbours and Rivers in Queensland, the cost of raising 6½ million cubic yards by dredgers in 12 years, averaged 7·51*d.* per cubic yard, say 5·70*d.* per ton. The price varied very considerably according to the quality of the material and the distance to which the spoil had to be carried. The lowest cost was 3·49*d.* per cubic yard at Cairns. In the narrows at Gladstone the cost was 27·83*d.* per cubic yard, the material being of an extremely hard and obstinate nature.

New South Wales.—A report made by Mr. C. W. Darley, the engineer-in-chief of the rivers and harbours, to the Legislative Assembly, as to the dredging operations carried on in 1889 and 1890, states that the plant used then consisted of 14 single and double ladder bucket dredgers capable of dredging at depths varying from 35 feet, 17 steam-tugs, 2 steam hopper barges, 2 sand-pump dredgers, and 18 Priestman grabs. In addition to which there has since been added to the fleet a twin-screw double sand-pump hopper dredger capable of carrying 500 tons, which had been made by Messrs. Simons and Co. of Renfrew, and additional suction-dredgers.

The total quantity raised by the bucket-ladder dredgers in the two years was 6,663,942 tons, the cost being as follows:—

	Pence per ton.
Wages	3·2119
Coal	0·4420
Repairs	0·9515
Stores and incidentals	0·4596
Dredging	5·0650
Towing	1·8230
Total	6·8880

The distance the material had to be conveyed is not given, but the greater part of it had to be carried out to sea. The dredgers were employed at Sydney, Newcastle, The Manning, Richmond, Hunter, Clarence, Bellinger, and other rivers. The smallest cost of dredging only was 2·199 for sand and mud raised at Newcastle, and the highest 26·823 for dredging sand in the Clarence river, wages amounting to 13·828, and repairs 8·121, and coal 1·612. The average cost of the working of fourteen Priestman grab dredgers in raising 571,139 tons of sand, gravel, and clay, was 7·3745*d.* per ton; the maximum average of any one grab being 14·385*d.*, and the minimum 3·017*d.* The cost of working five grabs employed in lifting 131,790 tons, consisting principally of the *débris* rock blasted, many of the pieces weighing from 3 to 4 tons, was 11·529*d.* per ton. The maximum of any one grab was 16·087*d.*, and the minimum 8·181*d.* per ton. The cost of raising and conveying on to the land 837,000 tons of sand and silt was as follows:—

	Pence per ton.
Wages	1·1920
Coal	0·2669
Repairs	0·4397
Stores and incidentals	0·1820
Total ...	2·0806

The cost of the coal varied from 6*s.* 2*d.* per ton to £1 6*s.* 8*d.*, the average being 12*s.* 4½*d.* The wages of the engineers varied from £12 to £20 a month; of engine-drivers, £10 to £13; firemen, £9 to £12; and other men in proportion.

American Lake Canals.—The average tenders received recently for dredging for the 21-feet channel between Duluth and Chicago and Buffalo were as follows: For 380,000 cubic yards of sand, gravel, and hard pan in Little Mud Lake, 1*s.* 7*d.*; for 950,000 yards of clay and sand at St. Clair flats, 11½*d.*; for 2,900,000 yards of clay and sand at Grosse Point, 1*s.* 2*d.*; for 1,086,000 yards of sand and gravel at the mouth of the Detroit, 1*s.* 6*d.*; and for 90,366 yards of limestone rock at Sailors' Encampment, 14*s.* 10*d.* (the lowest tender for this was 10*s.* 1*d.* per yard).

Bilbao.—In the improvement of the harbour here, and dredging a channel 3280 feet long and 18 feet below low water in 1876, about three-quarters of a million cubic yards of sand and mud had to be removed and raised from the barges 21 feet,

and discharged into the old river channel. A central-ladder dredger, capable of raising 800 tons a day, was used, and the material was raised from the barges by skeps raised and lowered by a 12-H.P. portable engine. The average cost per cubic yard, as given by Mr. Barron, the resident engineer, was—

	d.
Dredging and filling barges	2·10
Barging	1·61
Discharging barges	3·41
	7·12

or about 5·55*d.* per ton.

Danube.—The dredging in the Sulina channel, the material consisting of 1,749,392 cubic yards of clay and sand, cost, with a bucket dredger of 40 H.P., 2·414*d.* for dredging, and 1·597*d.* for transporting 2 miles; a total of 4·011*d.*, equal to about 3*d.* per ton. For raising and removing 3,284,834 cubic yards with a suction-pump, the average cost was 2·402*d.* per cubic yard, or about 1·825*d.* per ton.

River Weser.—About 14 million cubic metres have been removed since the improvement works commenced in 1882, the quantity during the last few years being over 4 million cubic metres a year. The dredging is carried on night and day by aid of the electric light for ten months in the year, being interrupted during the rest of the time by the ice. There are employed: 6 bucket dredgers capable of raising 120 to 250 cubic metres an hour, 2 suction dredgers, 3 chain dredgers with driving machines lifting 150 to 180 cubic metres an hour, 22 steam hoppers, 5 tugs, and 60 barges. The material is deposited by the hopper barges at the back of the training walls so long as the depth of the water will allow of this being done; but when it becomes too shallow, the material is deposited by the hoppers at the side of the channel, and raised by buckets and chains and discharged through sheet-iron tubes 1·64 foot diameter over the walls, the average distance being 1500 feet. Water is discharged into the pipes by a centrifugal pump at the rate of 9 of water to 1 of material. In some cases the mud is raised by the pumps through suction-pipes. The cost of the dredging and removal by the transporting-machines on to the land is 0·29 marks per cubic metre, or, including interest on outlay and depreciation and management, 0·45 marks.

This is equal to about 3·50*d.* per ton for the dredging and deposit of material, and 2·80*d.* for interest and depreciation.

Amsterdam Canal.—The suction dredgers used in the construction of this canal had centrifugal pumps 4 feet diameter, with 18-inch suction and delivery pipes, the pumps running at 180 revolutions a minute. The pipes were fixed between guide timbers fixed to the end of the vessel, and tackle provided for raising and lowering them. The engines were worked up to about 55 H.P., and 1½ ton of coal was used a day. The cost of the vessel and pump was £5000. Each machine raised and delivered about 1300 tons of sand a day into barges, at a cost of about 1½*d.* per ton.

Dunkirk.—The dredging in the sea outside the jetties, amounting to over 600,000 cubic yards a year, is effected by screw-hopper suction dredgers. This work was formerly let by contract, the price at first being about 1*s.* 9*d.* per ton; this was gradually reduced to 7·28*d.* The work was then taken in hand by the authorities, and the cost reduced to 1·46*d.*, including everything except plant. The dredgers used were sand-pump hoppers, having a suction-pipe on each side and two pumps. The hopper capacity is 314½ cubic yards. The pumps are driven by engines of 165 I.H.P., giving 120 revolutions a minute to the pump and 106 to the screw. The vessel can steam six knots empty and five loaded, and requires a crew of eight men. The pump is 5 feet 1 inch in diameter, and discharges 11,000 gallons a minute. The mixture pumped contains 4 to 10 per cent. of sand, which settles in the hoppers. A swell of 2 feet does not stop the work. The cost of the dredging for wages, coal, and repairs is 1·03*d.* per cubic yard, and for transport 3 miles, 0·426*d.*; total, 1·456*d.* The dredgers cost £5600 each. Dredging in the basin by contract with bucket dredgers, and conveying 3½ miles, cost 10·90*d.* per cubic yard, and 8·01*d.* in the tidal harbour. The difference of measurement between the material *in situ* and when measured in the barges varied from 25 to 45 per cent., according to the age of the deposit. The cost of pumping up sand and conveying it through long floating pipes on to the land is 1½*d.* per ton.

Ostend.—The removal of 325,000 cubic yards of sand in the open sea off the coast of Belgium, for deepening a channel across the Stroom bank by suction-hopper dredgers, cost 3·04*d.* per cubic yard, or say 2·18*d.* per ton.

Boulogne.—The dredging outside the piers here, commenced in 1883, was let by contract. Steam-hopper dredgers fitted with pumps and suction-pipes were used for raising the sand to be removed. The distance the material had to be removed was two miles. The contract price varied from $6\frac{1}{2}$*d.* to $7\frac{1}{4}$*d.* a cubic yard measured in the barges, say 4·68 to 5·22*d.* per ton. The actual cost of the work, exclusive of any allowance for the use of the dredgers, was 3·34*d.* per cubic yard, equal to 2·40*d.* per ton. It was found that the dredgers could continue working when the head waves did not exceed 3 feet, and the cross-waves half this.

In the harbour, bucket-ladder dredgers discharging into hopper barges were used, the distance the material was conveyed being two miles. The contract price for removing mud and sand was 12·28*d.* per cubic yard measured in the barges; for hard Kimmeridge clay, 32·38*d.*; for rock lying in shallow beds, which could be operated on by the buckets of the dredger, 70·40*d.* These prices may be taken as about equal to 9·21, 24·60, and 56·32*d.* per ton. It was considered that the work could have been done at less cost if more powerful machinery had been employed.

The Severn.—In the works recently carried out for improving this river below Worcester, under the direction of the late Mr. H. J. Martin, about 12,000 cubic yards of marl rock had to be removed. This was effected by an ordinary bucket-ladder dredger, having steel claws on the bucket-chain, one pair of claws being placed between each two pairs of buckets. The cost of removing the rock and depositing it on the river-bank cost on an average 1*s.* 3*d.* per cubic yard, say 11·40*d.* per ton. This included wages, coal, repairs, and all other expenses. The silt and soft material cost 6*d.* per cubic yard, or 4·32*d.* per ton for dredging and depositing.

In the improvements which were previously carried out in this river by Sir W. Cubitt about 1842, the rock was removed by blasting. Holes were drilled 6 feet apart and 2 feet below the surface to be dredged. A $2\frac{1}{2}$-inch iron pipe was driven into the marl a few inches, and the holes bored by jumpers and augers passing through it. In the holes cartridges covered with canvas were inserted and fired by a Bickford fuse. The cost was 4*s.* per cubic yard for loosening and dredging.

Sydney Harbour Blasting.—For removing rock under water

at these works in 1874, an account of which is given in a paper by Mr. Keeling in the '*Proc. Inst. C.E.*, vol. xi., gunpowder was first used, and subsequently dynamite. The cost with the gunpowder was 5*s.* 6*d.* per cubic yard, and with dynamite 4*s.*, made up as follows:—

Removing 10 cubic yards of marl rock and hard red sandstone 3 feet in thickness and 12 feet under water

	£	*s.*	*d.*
Drilling 5 holes, 15 feet @ 6*d.*	0	7	6
Dynamite, 5 lbs. @ 2*s.* 2*d.*	0	10	10
Five detonators and wire @ 6½*d.*	0	2	8
Five canvas bags @ 1*d.*	0	0	5
Dredging 10 cubic yards @ 1*s.* 6*d.*	0	15	0
Interest on plant, sharpening tools, etc.	0	3	4
Total ...	1	19	9

The holes were drilled from a raft 40 feet long by 20 feet broad. A wrought-iron pipe was carried through the floor of the raft until it rested on the rock. Within the pipe a jumper 21 feet long and 1¼ inch diameter was inserted to bore the hole in the rock. The drill was 2¼ inches in breadth; the jumper was attached to the end of a beam suspended in the centre from a frame fixed on the pontoon. One man held the jumpers and two men worked a rope attached to the other end of the beam, by which action the jumper was alternately raised and lowered. The pipes were perforated at the bottom, which allowed the holes to be bored to the required depth without the aid of an auger to clean them out, the action of the jumper acting as a plunger and effecting the removal of the pulverized rock.

The dynamite was placed in a calico bag 9 inches long by 2¼ inches in diameter, into which was inserted an electric detonating fuze. The charge of dynamite was wrapped in hay and lowered into the hole through the pipe, and the pipe removed. Very little tamping was required, the 12-feet head of water being nearly sufficient in itself. The fuse was exploded by Siemen's small "dynamo-electro mine exploder."

Blyth Harbour Blasting.—Gunpowder was also first tried by Mr. Kidd here in 1884, and afterwards abandoned for Nobel's blasting dynamite and gelatine placed in water-tight tin cases 2 inches in diameter, closed at the top with wood plugs. No tamping was used. The boring was done by hand. The cost of

boring and blasting 24,500 cubic yards of yellow sandstone rock and shale to a depth of 15 feet, a part of which was dry at low water of spring tide, and covered 14 feet 6 inches at high water, the depth given at the completion of the work being $29\frac{1}{2}$ feet, was 1*s.* 9*d.* per cubic yard for boring; 1*s.* 4*d.* for explosives; and dredging and conveying, including repairs, 3*s.*; or a total cost, exclusive of any allowance for plant, of 6*s.* 1*d.* The proportion of explosive was 0·853 lb. per cubic yard of rock removed.

The broken rock was dredged up by a bucket-ladder dredger of 25 H.P., which lifted on an average 6 tons of rock an hour. A Priestman grab was also used for the removal of large pieces of rock, many of which weighed from 1 to 2 tons. The material was conveyed 3 miles to sea (*Proc. Inst. C.E.*, vol. xxxi.).

The St. Lawrence River.—For removing shoals of blue limestone studded with flint in this river in Canada, in a depth of 12 feet of water, increased to 17 feet, the contract price was 9·90 dollars (41*s.*) a cubic yard. The explosive used was nitroglycerine, and the charge was placed 12 to 15 inches below the required bottom. The holes were bored with Ingersoll drills, varying from $1\frac{3}{4}$ to $2\frac{1}{2}$ inches in diameter, having four cutting edges of steel. The motive power was supplied from a steam boiler on the barge from which the drills were worked. The cartridge was 15 inches long, $\frac{7}{8}$ inch in diameter, and placed in a tin tube $1\frac{1}{2}$ inch in diameter, and the charge was fired by electricity. The average charge per cubic yard was 1·32 lb., and the quantity of rock removed 34·600 cubic yards. The average depth of the bore-holes was 5 feet (*Proc. Inst. C.E.*, vol. lxxx.).

River Yarra, Melbourne.—For removing a shoal of hard basaltic rock, and deepening the channel from 12 to 19 feet, drills were used, worked from the deck of a pontoon stage, and driven by compressed air. The explosive used was Nobel's No. 1 dynamite, placed in oiled calico cartridges in charges varying from 3 to 8 lbs. The holes were charged by a diver. Sling-chains and skeps filled by the divers were used for raising the material. The work lasted $3\frac{1}{3}$ years, and cost £17,351, the plant costing £3,597 in addition. The quantity of rock removed, 20,087 cubic yards; 22,191 cubic yards of clay being also taken away. The cost of boring, blasting, and placing the rock in barges was 12*s.* $3\frac{3}{4}$*d.* per cubic yard. Ten tons of dynamite were used (*Proc. Inst. C.E.*, vol. lxxiv.).

Hell Gate, New York Harbour.—The most extensive submarine blasting operation ever undertaken for the improvement of a harbour was that for the removal of the rocks known as Hell Gate, which obstructed the passage between New York Harbour and Long Island Sound. The works for the final operation in removing the middle reef consisted of the excavation of 21,669 feet of galleries through the rock, of an average section of 10 feet square, and involving the removal of 80,232 yards of rock by blasting. The total quantity of reef and pillars remaining to be shattered by the final explosion to a depth of 30 feet amounted to 270,717 cubic yards. The number of cartridges placed in the holes was 42,500, containing 240,399 lbs. of an explosive called rackarack, consisting of potassium chlorate and nitro-benzol, and 42,331 lbs. of dynamite. The cost of the final explosion was £22,190, the total expenditure in breaking up the reef being £218,612, exclusive of removing the shallow rock. The cost per cubic yard averaged 12*s.* 5½*d.* The total estimated cost of the Hell Gate improvement works amounted to £1,070,650. The works for breaking up the middle reef rock extended from June, 1875, to October 10, 1885, when the final explosion took place (*Proc. Inst. C.E.*, vol. lxxxv.; *The Engineer*, vol. 42).

"Dredging Operations and Appliances," by J. Webster, *Minutes of Proceedings Institution of Civil Engineers*, vol. 89; and also "Dredging Machine on the Stour," W. B. Hayes, vols. 1 and 2, 1837; "The Clyde," by J. Deas, vol. 36; "Dredging Carlingford Lough," J. Burton, vol. 44; "The Danube," C. H. L. Kuhl, vol. 65; "Dredging on the Tees," J. Fowler, vol. 75; "Dredging Calais and Boulogne," F. Guillain, vol. 80; "Dredging at Swansea," W. Capper, vol. 103; "The Von Schmidt Dredger," G. Wiggins, vol. 104; "Dredging and Dredge Plant," by A. C. Schonberg. "Inland Navigation Congress" (Manchester, 1890).

CHAPTER XI.

THE REQUIREMENTS OF NAVIGATION.

As the object in carrying out works in tidal rivers is to improve them for the purposes of navigation, it is essential that, before any attempt is made to advise as to the method to be pursued in obtaining the desired conditions, a knowledge of the requirements of a vessel in navigating a tidal channel should be acquired.

The following may be taken as the chief matters to be taken into consideration by an engineer in designing works for improving the access to a port:—

Requirements of Navigation.—I. The character of the shipping which frequents the port, or which will be attracted by increased accommodation.

II. The depth of water required in the channel for the class of vessels trading to the port.

III. The time the depth must be maintained.

IV. The distance of the port from the sea, and the time required to navigate the river.

V. The velocity of the current, and its effect in increasing or retarding the progress of the vessel.

VI. The draft of vessels in relation to the quantity of cargo carried.

VII. The depth required beyond the actual draft of the vessel to enable her to pass over a bar, to steer in the channel of the river, or pass over the sill of a lock.

VIII. Where the distance from the sea is great, the provision for mooring vessels afloat at some point between the sea and the harbour.

IX. The minimum radius of curvature round which vessels can be safely navigated.

X. The length and beam of vessels in relation to the size of lock required for docking.

XI. The length of quays required to discharge a given tonnage.

Depth of Water.—With regard to the second and third matters, it is a very great advantage to steamers engaged in the passenger trade if the depth of the water in the channel is sufficient to enable them to arrive and depart at fixed hours, and consequently at any state of the tide. Vessels which trade with ports situated at long distances away, such as those in the Pacific and Atlantic, are generally of the largest class, and require a deeper draught than those whose chief trade is with the Continent or in the coasting trade.

In Appendix XI. will be found a list of all the chief ports in the kingdom, with the number of vessels entering and their tonnage for the year 1891. From this it will be seen that, although London has the largest tonnage of any port in the kingdom, the average tonnage of the vessels is only 256 tons, or a little more than half that of Cardiff, which with 494 tons has the highest average; or of Liverpool with 489; or of the Tyne ports with 480 tons. Bristol has only an average tonnage of 159½ tons; while Hull, with a less number of vessels, has an average of 458, and Grimsby 412 tons; Dundee, with only 1287 vessels, has an average tonnage of 454; and Granton, with only 510 vessels, of 467 tons. In the larger ports the average is brought down by the small coasting-vessels.

The small coasting-vessels under 50 tons register constitute nearly 28 per cent. of the whole ships in the kingdom, or, taking up to 100 tons, nearly 54 per cent. Those between 100 and 800 constitute 21 per cent.; and between 800 and 2000 tons 21 per cent., leaving only 1½ per cent. above 2500 tons (see Appendix).

In some tidal rivers the navigation depends entirely on the rise of the tide, the channel being practically dry at low water; in others, vessels of small tonnage only can navigate the river at neap tides, those of large tonnage being only able to reach the docks at spring tides, and, if arriving during neaps, have to lie in the roadstead or lighten their cargoes into barges. In other rivers there is depth for small craft at low water, and for larger vessels when the tide is half flood, leaving a much longer period for the navigation of the river than when the depth required is due entirely to the tide. In rivers in the best condition for navigation, the depth of water in the channel is sufficiently deep for its navigation by all vessels at all times; the rise of the tide is

moderate, so as not to require expensive constructional works; and the velocity of the currents, whether of ebb or flood, not so great as unduly to impede the progress of vessels.

Size of Vessels.—The character of shipping has entirely altered within a comparatively short period. Sailing vessels have, to a very large extent, been superseded by steam. The size of the craft has very greatly increased, and for the present appears to be likely to continue to do so. In fact, it may be said that the limiting factor of draught is the depth of water available at the principal ports in this and other countries, and that as this is increased so will the size of vessels continue to become greater. Thus, while the number of vessels in the merchant service is smaller than it was a few years ago, the total tonnage has considerably increased. Taking the past five years, the number of vessels on the Register is 1034 less, while the tonnage is 1,845,000 tons more. The average size of all the vessels built now is 540 tons, or, taking steamers only, 1000 tons. Taking the vessels classed at Lloyd's, in 1891 the average size of steam vessels was 2100 tons against 1991 in the previous year, and of sailing vessels 1696 tons against 1783 in 1890.

Taking the whole of the vessels on the British Register as given in the Board-of-Trade returns, there were in 1881 38,752 vessels of an aggregate tonnage of 8,575,560 tons, or an average of 221 tons per vessel. In 1891 the number of vessels had decreased to 36,085, and the tonnage increased to 9,961,574, giving an average of about 276 tons to a vessel.

When the navigation of the country was conducted in wooden sailing vessels of small tonnage, as compared to those now in use, it was sufficient to provide berths and quays in the channel, where a vessel could lie dry or only half water-borne at low water and discharge her cargo. The introduction of iron vessels of great length in proportion to beam, with heavy boilers and machinery, made it desirable that they should always be afloat, and a wet dock or floating accommodation is now a necessity. The construction of the first wet docks in the Thames was not undertaken so much for the purpose of providing floating accommodation as for putting the ships in a secure place where the robberies of valuable cargoes, which took place in the open river, could be prevented. The increase in the size and draught of vessels which has taken place has necessitated the gradual reconstruction of harbour works, which were quite sufficient for their purpose

when first made; the dredging and deepening of the channels; and the building of docks with larger locks and deeper sills.

The change that has taken place will be better realized by a comparison of the trade of the Thames during the last and present centuries. In 1700 the number of vessels navigating the Thames was 6897, having a total tonnage of 435,135, and an average tonnage for each vessel of 63·09 tons. In the middle of the last century the number of vessels had increased to 8078, and the average tonnage to 92·35 tons. At the end of the century 13,444 vessels entered the river, of a total tonnage of 1,762,898, and an average tonnage of 130·39 tons; or, taking only those vessels which traded to foreign ports, the average tonnage in 1700 was 96 tons; in 1751, 132 tons; and 1794, 196 tons. The number of vessels entering the port of London in 1891 was 51,632, of an aggregate tonnage of 13,216,946 tons, of an average tonnage of 256 tons.

At Leith, at the beginning of the present century, Mr. Telford, in advising as to the dock accommodation and size of locks required, found that 3484 ships which entered that port were under 200 tons, and drew under 10 feet of water; 135 were between 200 and 400 tons, drawing from 11 to 14 feet, and only 4 above 400 drawing 15½ feet. In 1891 3749 vessels entered, of an aggregate tonnage of 1,247,769 tons, the average tonnage of each vessel being about 333 tons. The depth of water on the sill of the lock at spring tides is 26 feet 6 inches, and this is not found sufficient, and is about to be increased.

Modern Atlantic liners, such as the *Campania* and *Lucania*, are 625 feet in length, 65 feet beam, and draw 26 feet. The gross tonnage of each is 12,950, and the I.H.P 30,000. The *Majestic* and *Teutonic* are 582 feet long, and 57½ feet beam, and have a draft of 26 feet. The *Paris* and *Rome* are 560 feet long, and draw 24½ feet.

Modern vessels not only require increased accommodation on account of their larger dimensions, but greater depth and improved waterways, in order that they may have quick despatch. The running expenses of a large steamer are such that it is vital to its success that there should be as little delay as possible in navigating the port, waiting for spring tides, or in discharging cargo. In sailing ships, it used to be, and is still to a large extent, the custom to discharge the crew as soon as the ship was moored in dock; the expenses under these circumstances of the

vessel in port are small. It is, however, more difficult to replace the crew of a steamer, and they are generally retained in port, and wages have to be paid. The owners, therefore, require that the stay in port shall be as short as possible.

Tonnage of Vessels.—The modern design of steamers and sailing vessels has resulted in very largely increasing their capacity for carrying cargo in comparison with their total cubical capacity, as determined by the present method of measurement. The measurement on which ships are entered at the Custom House is known as the *registered* tonnage, on which all dues and tolls are paid. This is defined by the Merchant Shipping Act of 1854 (17 & 18 Vict. c. 104, clause 21), and is based on the cubical contents of the hold of the vessel, after making allowance for the accommodation of the crew. In steam vessels, from the gross tonnage as found above, an allowance is made for the space occupied by the machinery used for propelling the ship, and the cubic contents found after making this deduction is "the net tonnage" on which dues are paid. Approximately, a register ton is equal to 100 cubic feet.

The quantity of cargo which a vessel will carry, or her "tons burden," greatly exceeds her register tonnage, and varies with the build of the vessel and also with the class of cargo. Selecting a large number of vessels from Lloyd's Register, and taking coal as a cargo, the average quantity the vessels are capable of carrying for every 100 tons register is as follows:—

	Steamers.	Sailing vessels.
	Tons of cargo per 100 tons register.	
Wood vessels	182	168
Iron "	197	140
Steel "	216	158

In Appendix No. XII. will be found an abstract showing the number of vessels frequenting all the principal ports of the kingdom, with their total and average tonnage.

Draft of Vessels.—The quantity of cargo which a vessel can convey to a port depends not only on her size, but on the depth of water in the channel which she navigates. The navigable depth of water is therefore the guiding factor in the class of shipping which frequents any particular port. While the engineer has been providing for the larger cargoes now carried by increasing the depth of the channel and the quantity of water available over the sills of the locks, the shipbuilder has been

designing vessels which, without adding to the draught, will carry increased cargoes. The small draught of the Suez Canal when first constructed gave a great impetus to this movement. The depth of the Canal has since been increased, and the average draught of the 4206 vessels which went through in 1891 was 2068 tons. From a report made by Mr. J. Walker in 1835, a vessel of 500 tons register had a draught of from 13 to 16 feet; of 500 tons, from 17 to 18 feet; and of 700 tons, 19 to 21 feet. The draught of vessels of the same registered tonnage now, would be, for the 300-ton vessel, 12 feet; for the 500-ton, 14 feet; and for the 700-ton, 16 feet.

Vessels may be specially designed to carry large cargoes on very light draughts. Thus, for the lake and canal service in Canada and America, steamers are constructed capable of carrying 3000 tons on a draft of 14½ feet, and 4000 tons on a draft of 17 feet. These vessels are about 350 feet in length, 45 feet beam, with 24½ feet depth of hold.

Although no exact rule exists, and vessels vary very considerably in their draught, the following may be taken as approximately that of modern vessels:—

Registered tonnage.	Draft in feet.
60–80	8
100–150	10
200–300	12
400–500	14
500–600	15
600–700	16
700–800	17
800–1000	18
1000–1200	19
1200–1500	20
1500–2000	22
2000–3000	23
3000–4000	24

It has been stated that the capacity of a port varies as the cube of the navigable depth of water in the channel. This rule may apply to ports frequented by the smaller class of vessels, but with the larger tonnages the value of the port increases more rapidly with the depth than by this law. It will be seen from the above table that, in tidal rivers of the smaller class, an increase of one foot in the navigable depth, or about one-fourth, gives accommodation for 100 tons of increased carrying capacity. For ports frequented by vessels of 1000 tons register, one foot

extra depth, or about one-twentieth, increases the carrying capacity 200 tons; and in ports where 2000-ton vessels can go, an increase of one-twenty-second in depth increases the carrying capacity 500 tons, or about one-fourth. Beyond this the advantage given by depth increases very rapidly.

The annual statement of Navigation and Shipping, issued by the Board of Trade for the year 1891, an abstract of which is given in Appendix XI., shows that, including coasting vessels, about 70 per cent. of the ships belonging to the British merchant service do not exceed 500 tons register. The average draught of these may be taken at 15 feet. About 96 per cent. of the whole British mercantile marine is under 2000 tons register, the draught of the largest of these averaging about 22 feet. The vessels above this draught consist of the large passenger-steamers engaged in the American and colonial trade, and a few large sailing ships and cargo-steamers built for special services.

Although the bulk of the ships which frequent a port may only have a maximum draught of from 16 to 18 feet, provision must be made for the larger class of vessels, as such cargoes as grain, maize, linseed, etc., are almost invariably brought over in vessels drawing from 18 to 22 feet.

A vessel draws more water in a river filled with fresh water than in the salt water of the sea. A vessel drawing 20 feet in salt water will be immersed 20 feet 7 inches in fresh water. To find the difference of the increased immersion of a vessel passing from salt to fresh water, the draught may be multiplied by 1·029, and by 0·972 when passing from fresh to salt water.

In addition to the actual draught of the vessels, a certain margin must be allowed under the keel. In passing through a lock an allowance of one foot is generally found sufficient, or even, on a rising tide, 6 inches. In navigating a river channel where the water is smooth, unless a vessel has two feet under the keel she is said to "smell the ground," and will not steer properly, although in practice pilots bring up vessels with half this margin, and even where there is only 6 inches to spare over short lengths of shoals. Where the margin is so small there is considerable risk of the vessel grounding, especially on a falling tide, and an engineer should never calculate on less than two feet beyond the draft of the vessels. In estuaries and in crossing bars, where there is a swell, the least margin pilots consider safe is 4 feet. When the sea is rough, and the waves of any size, this

would not be sufficient. The depth of water on a bar at a given state of the tide being known, a deduction must be made for the *'scend* of the vessel, or the vertical distance she descends below the mean level of the water when passing through the waves. Mr. Meik made several observations in Sunderland harbour, to ascertain what the 'scend of a vessel was in rough weather, and he arrived at the conclusion that small colliers passing through a ten-feet wave would 'scend $7\frac{1}{2}$ to 8 feet; small colliers, 180 feet long, passing through the same wave, would only 'scend 5 feet, and that the 'scend may be taken, on an average, at two-thirds the greatest lift for ordinary colliers, and half the lift of the wave for larger steamers. The lift of the wave being taken as the space from the trough to the crest.

Width of Channel.—The width of a channel required for navigation, although a matter of less importance than the depth, yet requires consideration. There must not only be room for vessels going up to pass those going out, but a narrow channel adds to the difficulty of navigating the vessel, and diminishes the speed. Up to a certain limit, the less the sectional area of the water-way proportional to the immersed sectional area of the vessel the greater will be the power required to drive the vessel through the water. In confined channels, it is generally considered that, for a vessel to move freely, the sectional area should be such as to give a depth of 3 feet under the bottom, and that the area should be six times the cross-section of the submerged portion of the boat. For a cargo-steamer of 1500 tons register, this would require a channel about 230 feet wide by 23 feet deep.

Distance of a Port from the Sea.—The distance a port is situated inland increases its advantage as a centre of distribution and its commercial value. The increased length of waterway involved, however, adds to the difficulties and requirements of the navigation. In such cases it becomes important to know the time a vessel will take to navigate between the port and the sea, and the depth of the water that will be found throughout her course, which of course will vary with the state of the tide. Thus a vessel having to traverse a tidal channel 30 miles long, and entering from the sea at high water, would have the tide falling as she advanced, and the depth of water become less the further she proceeded.

To ascertain the maximum draught of the vessel that can

navigate a channel under such conditions, it is desirable to have a tidal diagram showing the navigable depths throughout the course at all states of the tide (see Fig. 35).

A navigation diagram may be constructed in the following

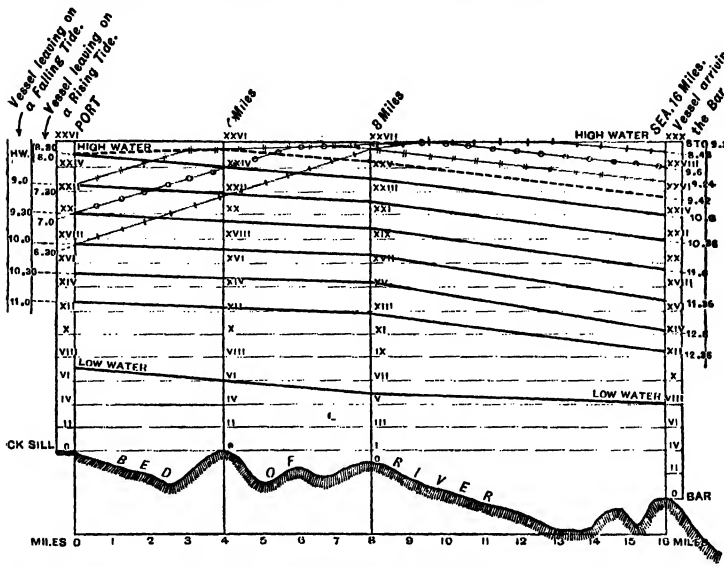


FIG. 35.—Diagram showing depth of water in a tidal channel available for a vessel leaving a port and going out to sea.

Note.—Vessel taken as going 6 miles against tide, 8 miles at slack water, and 10 miles with the tide.

manner. The height of the tide at any given point and at any given time being ascertained from the diagram of the tides, the shoalest places in the river are selected, and the heights above these set out on a scale on the diagram. Supposing a vessel to leave the dock at 7.30 o'clock, or one hour before high water, with 22 feet of water on the sill, and that the first shoal place is 4 miles down the river; going at the rate of 6 miles an hour, she will arrive there at 8.15, or at about high water, and have 25 feet of water over the shoal. By the time she arrived at the next shoal the tide would have fallen a little, but there would be 26½ feet of water there. She would now carry the tide with her, and proceed over the ground at an increased rate, and would arrive at the bar at 9.24, and have 26½ feet of water. If the vessel left at an hour after high water, she would have 20 feet on the dock sill, and, carrying the tide with her all the way, have 19½ feet at the first and second shoal places, and 19¼ feet at the bar.

In river channels it may be assumed that the speed of a vessel under steam will not exceed 10 miles an hour, but as a rule it may be taken at 8. The actual progress over the ground will be increased or decreased depending on whether she is going with or against the current, and in proportion to its velocity. Thus a steamer with an 8-knot speed, going with the tide having a 2-knot current, will progress over the ground at the rate of 10 knots, or if against a 2-knot current, then her progress will be 6 knots.

Lay Byes.—In cases where the distance to be traversed is great and the navigation is dependant on the tide, it becomes essential that provision should be made at some point, about midway of the channel, for a lay bye where the vessel can moor afloat and wait for the following tide. As river channels seldom afford sufficient width for a vessel to swing with the tide, provision must be made for moorings from both stem and stern, and this can be most readily done at a mooring stage, against which the vessel can lie.

Unless a natural pool, having sufficient depth for the vessel to lie afloat at low water, exists, it will be necessary to provide a berth by dredging, and this is most likely to maintain its depth if it be situated in a concave bend of the channel.

Dock Accommodation.—The accommodation required for docking vessels involves considerations of construction which is beyond the scope of a work on tidal rivers. It may, however, be stated that a dock lock 200 feet long and 30 feet wide will admit of the entrance of vessels up to about 500 tons register; 250 feet long by 35 feet wide, of vessels up to 1000 tons; 300 feet by 50 feet, up to 2000 tons; 350 feet by 50 feet, up to 3000 tons; 400 feet by 60 feet, up to 4000 tons.

To accommodate the large Atlantic liners, the Mersey Dock Board are having locks built 700 feet long, 100 feet wide, with 40 feet on the sill at high water. The lock at the Tilbury Dock on the Thames is 555 feet long, 80 feet wide, and has 26 feet on the sill at low water, and 45 feet high water.

The length of a lock is not necessarily the measure of capacity of the dock. In small docks the larger class of vessels can only get up on the spring tides when the water in the river and the dock at high water is level. It is an error to make the lock out of proportion to the size of the dock. This leads to a waste of water in docking small vessels in and out

at neap tides, and to the lowering of the water to an inconvenient level below the quays.

It is generally estimated that 1 yard of quay in a dock will give accommodation to a registered tonnage of from 300 to 400 tons in the course of the year.

Wrecks.—It occasionally becomes necessary to remove from a tidal river vessels which have become wrecked in the fair way to the impediment of the navigation. Under the Removal of Wrecks Act of 1877 (40 & 41 Vict. c. 16, and amended by 52 Vict. c. 5), the local harbour authority at any port have the power to clear away a wreck, and to be reimbursed out of the sale of the material or cargo recovered so far as sufficient for the purpose. Some ports have obtained further powers, and can enforce payment by the owners of all expenses incurred in the removal.

The first duty of an authority, on a wreck occurring, is to mark the site with a green buoy having the word "wreck" painted on it; the buoy, where practicable, to be laid near to the side of the wreck next to mid-channel. When a wreck-marking vessel is used, she carries a cross-yard on a mast with two balls by day, placed horizontally not less than 6 nor more than 12 feet apart, and two lights by night similarly placed. When a barge or open boat is used, a flag or ball may be shown in the daytime.

The Thames Conservancy have the most complete wreck-raising plant in the country, the amount expended annually in removing wrecks from the Thames amounting to between £5000 and £6000.

There are several wreck-raising associations who undertake to raise sunken vessels, their chief object being the preservation of the property of the shipowners and underwriters. These associations do not enter into contracts for a specified sum, but charge their employers the cost of the work, whatever it may be. The principal of these is the London Salvage Association, the Liverpool Salvage Association, and the Glasgow Salvage Association.

The methods used in raising sunken ships are too various to detail here. Generally the process for small vessels is to lift them by means of chains or wire rope placed under the keel and attached to barges on either side. The vessel is then lifted by the tide, and floated to a berth on the shore. This process is

also assisted by placing empty barrels in the hold, taking care so to arrange them that they do not lift the deck. With larger vessels divers are employed to remove the cargo if practicable, and then to cover the hole which caused the leak with shields of iron or wood and with a quick-setting cement; and, having closed the water-tight compartments, to pump out the water with centrifugal pumps. By the aid of these pumps, also, such cargoes as grain can be pumped out of a sunken vessel.

In some cases it is necessary to destroy the vessel by explosives, but this should be avoided, if possible, as sunken pieces of the vessel may become a source of danger to the navigation.

Where vessels have to be lifted, flexible wire rope is found more easy to handle than chain, and has less slack, so that less of the rise of the tide is lost.

The weight of an iron ship or steamer varies from about 0·70 to 0·80 of her gross registered tonnage. In addition allowance has to be made for the weight of the water filling those parts of the vessel rising out of the water, and, if a dead lift is attempted, the difference of the weight of the cargo and of the water in which it is immersed.

"Annual Statement of the Navigation and Shipping of the United Kingdom," issued annually by the Board of Trade: "Dock and Port Charges of Great Britain and Ireland," by R. Thubron (London: C. Wilson, 1877; Supplement, 1881); "The Shipping World Year-Book" (London: Shipping World Office); "Steamship Capability," by J. Wingate (Glasgow; P. Forrester); "Salvage and Wreck-raising," by J. J. Fletcher, C.E. (London, 1890: Shipping World Office).

CHAPTER XII.

BUOYING AND LIGHTING TIDAL RIVERS.

THE lighting and buoying of the coast of this country is under the direction of the Trinity House, London. The management of the buoys and lights of estuaries and tidal rivers devolves, with few exceptions, upon local harbour authorities. The information contained in this chapter is intended only to apply to this class of work.

Information as to lighthouses and the larger class of beacon lights will be found in the paper contributed by Sir James Douglas to the Royal Institution, and printed, with illustrations of lighthouses and lightships, in *The Engineer* of March 29, 1889; and also in the paper by the same author on "The Electric Light as applied to Lighthouse Illumination," in the fifty-seventh volume of the *Proceedings of the Institution of Civil Engineers.*

The development of steam power for propelling ships, and the increased size of vessels employed, has necessitated a more extensive and efficient system of lights and buoys, and a channel must be made as easy to navigate in the dark as in the daylight tides. The change also of the material of which buoys are constructed, and the invention of new methods of lighting, have tended to revolutionize the system that was in use a few years ago.

Formerly the lighting of the coasts and providing sea-marks was undertaken by societies or private individuals, who obtained royal charters giving powers to levy tolls on passing ships. The Trinity House Corporation commenced its existence as a society, established at Deptford by charter in the reign of Henry VIII., for the purpose of providing lights and beacons for the Thames and the southern district of the East Coast. Its full title is, "The Master Wardens and Assistants of the Guild

of the most glorious and undivided Trinity and of St. Clement, in the Parish of Deptford, Strond, in the County of Kent." Its first lighthouse was erected in 1680. Owing to the large increase in the shipping of the Thames, the revenue increased much more rapidly than the cost of maintaining the buoys and lights, and large sums were annually dispensed in charity. Under an Act passed in William IV.'s reign, the power given under the ancient charters for maintenance of lighthouses was withdrawn, and by this Act and the Merchant Shipping Act of 1854 the constitution of the Trinity House was enlarged. The entire duty of lighting and buoying the coasts of England and the river Thames now devolves exclusively upon the Trinity House.

The Corporation consists of a Master, Deputy Master, nineteen acting Elder Brethren, and an unlimited number of Younger Brethren. The Master and honorary Elder Brethren are always elected on the ground of eminent social position. The Deputy Master and acting Elder Brethren are elected by the Court of the Elder Brethren from such of the Younger Brethren as are possessed of the necessary qualifications, and have obtained the rank of commander in the Navy four years previously, or have served as master in the merchant service on foreign voyages for a period of not less than four years. The head-quarters of the Trinity House are in London, with branch establishments at Ramsgate, Harwich, Yarmouth, Cowes, Milford, and Holyhead.

In addition to the care of the lighthouses, sea-marks, and buoys in the Thames and on the coast from Berwick to Carlisle, the Trinity House has the duty of examining candidates for and licensing the Thames and Channel pilots.

The lighting and buoying of the Scotch coast and of the Isle of Man is under the direction of the Commissioners of Northern Lighthouses; and of the Irish coasts, of the Dublin Corporation. The lighthouses of both these trusts are under the supervision of the Trinity House, and the sanction of this Corporation has to be received before the erection of any new lights. The Board of Trade has a general control over the three boards, and before any exceptional expenditure can be incurred, the sanction of this Board has to be obtained. The Trinity House and the other lighthouse authorities have also a controlling direction over the lighting and buoying of all local

authorities, and it is their duty from time to time to inspect all local lights, buoys, and beacons within their jurisdiction, and report to the Board of Trade the result of such inspection, which reports are to be laid before Parliament. Before the erection by any local harbour authority of any new, or the alteration of existing lights, buoys, and beacons, the sanction of the Trinity House in England, the Commissioners of Northern Lights in Scotland, or the Corporation of Dublin in Ireland, must first be obtained.

The annual cost of maintaining the lighthouses, light-vessels, and buoys, including office expenses and superannuation allowances, is over £200,000 for England, £70,000 for Ireland, and £50,000 for the northern district; in addition to which is a large annual expenditure on new works. The light dues amount to over £500,000 a year.

The method of lighting and buoying estuaries and tidal channels is not subject to any statutable regulations, consequently a considerable diversity of practice prevails amongst the local authorities having charge of these. To vessels in charge of local pilots this is not of consequence, but it is obvious that if one universal system were in use it would be of great advantage to ships failing to obtain pilots, and to smaller craft using the navigation without their aid.

To obtain as far as possible uniformity, a conference was held by representatives of the Board of Trade, the Trinity House, and the Admiralty, and the following code of regulations agreed to for adoption in all cases where the buoys come under their direct management and control, and was recommended for adoption by all local authorities. In framing these regulations the shape of the buoys was more relied on than the colour as distinguishing the different parts of the channel. It is unfortunate, as liable to lead to confusion, that in determining the right and left hand side of the channel, the well-known rule that the right bank of the river is that to the right hand when going down the stream from the source to the mouth should have been departed from, and the right-hand side settled as that on the right hand when going up the channel.

Regulations for Buoying Channels.

The term "starboard hand" shall denote the side which would be on the right hand of the mariner either going with the main stream of flood or entering a harbour, river, or estuary from sea-

ward; the term "port hand" shall denote the left hand of the mariner under the same circumstances.

Buoys showing the pointed top of a cone above water shall be called conical, and shall always be starboard-hand buoys, as above defined.

Buoys showing a flat top above water shall be called can, and shall always be port-hand buoys, as above defined.

Buoys showing a domed top above water shall be called spherical, and shall mark the ends of middle grounds.

Buoys having a tall central structure on a broad base shall be called pillar buoys, and, like other special buoys, such as bell buoys, gas buoys, automatic sounding buoys, etc., shall be placed to mark special positions either on the coast or in the approaches to harbours, etc.

Buoys showing only a mast above water shall be called spar buoys.

Starboard-hand buoys shall always be painted in one colour only.

Port-hand buoys shall always be painted of another characteristic colour, either single or parti-colour.

Spherical buoys at the ends of middle grounds shall always be distinguished by horizontal stripes of white colour.

Surmounting beacons, such as staff and globe, etc., shall always be painted of one dark colour.

Staff and globe shall only be used on starboard-hand buoys; staff and cage on port-hand; diamonds at the outer ends of middle grounds, and triangles at the inner ends.

Buoys on the same side of a channel, estuary, or tide-way may be distinguished from each other by names, numbers, or letters, and, where necessary, by a staff surmounted with the appropriate beacon.

Buoys intended for moorings, etc., may be of shape or colour according to the discretion of the authority within whose jurisdiction they are laid, but for marking submarine telegraph cables the colour shall be green, with the word "telegraph" painted thereon in white letters.

Wreck buoys in the open sea, or in the approaches to a harbour or estuary, shall be coloured green, with the word "Wreck" painted in white letters on them.

When possible, the buoy shall be laid near to the side of the wreck next to mid-channel.

When a wreck-marking vessel is used, she shall, if possible, have her top sides coloured green, with the word "Wreck" in white letters thereon, and shall exhibit—

By day: Three balls on a yard 20 feet above the sea, two placed vertically at one end and one at the other, the single ball being on one side nearest to the wreck.

By night: Three white fixed lights similarly arranged, but not riding light.

In narrow waters, or in rivers, harbours, etc., under the jurisdiction of local authorities, the same rules may be adopted, or, at discretion, varied as follows:—

When a wreck-marking vessel is used, she shall carry a cross-yard on a mast with two balls by day placed horizontally not less than 6 feet, nor more than 12 feet, apart, and two lights by night similarly placed. When a barge or open boat only is used, a flag or ball may be shown in the daytime.

The position in which the marking-vessel is placed with reference to the wreck shall be at the discretion of the local authority having jurisdiction.

On the establishment of electricity as a practical illuminant, its use for lighthouse purposes necessarily engaged the attention of the Trinity House. About the same time a considerable controversy arose as to the respective merits of oil and gas as illuminants. The brilliant lights produced by a gas-burner invented by Mr. Wigham, and used on some parts of the Irish Coast, obtained a very strong feeling in their favour by shipowners. The improvement in the use of oil by the burners introduced by Sir James Douglas, combined with the economy of its use, gave this illuminant great advantages over either of the others.

The whole matter was referred by the Trinity House to a committee, and elaborate experiments were undertaken at the South Foreland, at a cost of £9000, for the purpose of investigating the relative merits of oil, gas, and electricity as illuminants. More than 6000 observations were taken, and the conclusion arrived at was (1) that the electric light was the most powerful under all conditions; (2) that the quadriform gas apparatus and the triform oil apparatus were about the same power when seen through revolving lenses, the gas being a little better than the oil; (3) that through fixed lenses the superiority of the gas-light

was unquestionable—the large size of their flame and their nearness together gave the beam a more compact appearance; (4) that the Douglas gas-burner was more efficient than the Wigham burner; (5) that for the ordinary necessities of lighthouse illumination mineral oil was the most suitable and economical illuminant; (6) that for salient headlands and places where a very powerful light was required, electricity offered the greatest advantages. Subsequently a further scientific examination of the matter was made, based on the experiments already carried out, by Sir George Stokes, Sir William Thompson, and Lord Rayleigh. Their report, while more favourable to gas, implied that this was outweighed by the greater simplicity and economy of oil; that the electric light far exceeded the others in the amount of light it gave out even in fog and haze. For prominent positions, where the light is used to guide the mariners from a long distance, the electric light is now admitted to be unquestionably the best. For fixed lights not requiring the same far-reaching brilliancy, oil, from the simplicity, or rather absence, of all machinery required for its application, still holds its own; while in situations which are appropriate to the construction of gas-making apparatus, gas has advantages, especially where a fixed intermittent light is required, by the facility with which the gas-flame can be suddenly turned on and off.

The navigable portions of tidal channels are marked out by buoys or beacons for day service, and by lights during the dark. These buoys and beacons are placed along the line of deep water or on prominent shoals and turns in the channels. No rule can be laid down for the distance apart at which buoys should be placed. This varies from a mile and a half in a wide estuary, where the larger class of buoys are used, to a tenth of this distance in narrow river channels, passing through sandy estuaries. For trained channels beacons are generally fixed on the training walls.

Buoys are known under the name of cone, can, nun, spherical, or pillar, according to their shape. The cone buoy floats with the broad part in the water, having the cone above the surface. The can buoy, on the other hand, shows a flat top above the water. The nun buoy is pointed at both ends, having the widest part in the centre, about the line of flotation; it is light and simple in construction, easily laid, therefore useful in shoal water where the buoys have frequently to be removed. The

spherical buoy, as its name denotes, shows a sphere above the water. The pillar buoy is the shape of a can, having a pillar rising above the flat top. The method of making these different shapes useful as sea-marks has already been described in the regulations for buoying. Formerly buoys were made of wood, but as in the case of ships, wood has been superseded by iron, and now steel is almost universally used in the construction of new buoys.

The object to be kept in view in designing the shape of a buoy is that it shall float upright, not only when the water is still, but when subject to waves and tidal currents, and show as large a portion of the superstructure as possible above the water. Long narrow buoys coming to a point, and having the moorings attached to this, even if riding upright in still water, almost invariably lie over when the tidal current is running, and roll considerably in rough water, making them bad sea-marks. By making the bottom flat and hollow, and so raising the point of attachment of the moorings, less strain is thrown on the mooring in rough weather. If the point of attachment is raised about half the depth of the floatation, the surface exposed to lateral pressure above and below is equalized. The buoy, therefore, when carried over by the current, has a tendency immediately to right itself, and if properly designed rides upright under all conditions.

The larger class of buoys exposed to rough seas are divided into two watertight compartments by a diaphragm plate, which diminishes the liability to sink when injured. They may also be made more secure by having strengthening plates at the water-line, where the buoy is most subject to damage from being run into. The following may be taken as the strength of the plates in general use by the Trinity House. The steel specified is to have an ultimate tensile strength of 30 tons to the inch, and a mean contraction of not less than 50 per cent. at the point of fracture. For the larger buoys, spherical or conical, 12 feet and 10 feet in diameter, the plates are specified to be of the following thickness: spherical portion and bulkhead, $\frac{3}{16}$ inch; waist, $\frac{5}{16}$ inch; bilge, $\frac{3}{8}$ inch; sides of the concave bottom, $\frac{1}{2}$ inch; crown of bottom, $\frac{3}{4}$ inch. For the small buoys ranging from 8 feet to 5 feet, the thickness is the same except the sides and concave bottom, which are $\frac{3}{8}$ inch, and crown of bottom $\frac{5}{8}$ inch. The plates are single riveted, the rivets having $2\frac{1}{2}$ inch pitch.

The buoys are tested with water to a pressure of from 5 lbs. to 7 lbs. per square inch. Buoys in sheltered estuaries and tidal rivers may be made of lighter plates than those in use by the Trinity House. Buoys are provided with a manhole in the upper part for the purpose of riveting in the first instance, and for any subsequent repairs. For large buoys the cover should be $\frac{1}{4}$ inch thick, with inside strengthening ring $2\frac{1}{2}$ inch by $\frac{3}{8}$ inch, the door being held in position by $\frac{1}{4}$-inch set screws spaced 3 inches apart. The joint is made with vulcanized india-rubber washer $2\frac{1}{4}$ inch by $\frac{1}{4}$ inch. The mooring ring, having 4-inch eye, is made from Low Moor iron not less than 2 inches diameter for the larger buoys and $1\frac{1}{2}$ inch for the smaller, and is riveted to three cross-bars or a strengthening plate 9 inches in diameter by $\frac{1}{2}$ inch thick, fixed to the bottom plate of the buoy by $\frac{5}{8}$-inch rivets; where there is a diaphragm the shaft of the ring is stayed to the plate. The cap at the top is made of $\frac{3}{8}$-inch plate, to which is attached a lifting ring $1\frac{1}{4}$ inch in diameter. A brass ferrule is tapped into one of the plates fitted with screw plug, for the purpose of attaching fittings for testing the buoy. After the buoy is completed and tested it should be gently and uniformly heated, and while warm coated externally and internally with linseed oil, and afterwards, when dry, painted outside with oxide of iron paint.

The weight of a steel buoy of the Trinity House pattern, with diaphragm and strengthening plate at the water-line, 10 feet high and 7 feet 9 inches in diameter, is about 35 cwt., and of a buoy 8 feet high 22 cwt. The price at which they can be made may be taken at £1 15*s.* per cwt., when steel plates are worth £8 10*s.*, making the cost of a 10-feet buoy £61, and of 8-feet buoy £38 10*s.* For small buoys, the material, bearing a less proportion to the workmanship, the price will be greater.

The cone buoy shown in Fig. 36 is of lighter construction, and has no dividing plate inside. The weight of this buoy, 10 feet high and 7 feet 3 inches diameter, with side plates $\frac{1}{4}$ inch thick, bottom plates $\frac{3}{8}$ inch, and upper $\frac{3}{16}$ inch, is $17\frac{3}{4}$ cwt., and of 8-feet buoy is $13\frac{1}{4}$ cwt.

The can buoy, Fig. 37, with crown plate $\frac{1}{8}$ inch, side plates $\frac{3}{16}$ inch, and bottom plate $\frac{1}{4}$ inch, weighs if 6 feet high $5\frac{3}{4}$ cwt., and if 4 feet $2\frac{1}{4}$ cwt.

The can buoy, Fig. 38, 7 feet 3 inches high and 6 feet widest diameter, made to match the cone buoy, Fig. 36, weighs $13\frac{3}{4}$ cwt.

The spider-legged buoy, illustrated in Fig. 39, shows very prominently above the water, and is adapted to mark the entrance to an estuary on the starboard side. When, however,

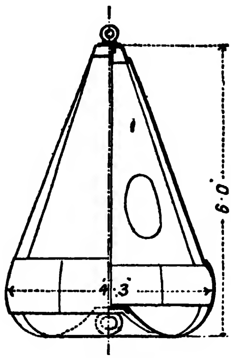


FIG. 36.

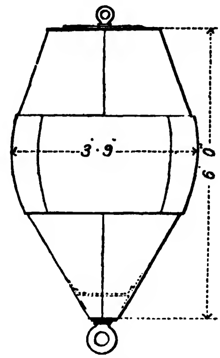


FIG. 37.

there is much sea, this form of buoy is difficult to lay owing to the encumbrance of the legs. A steel buoy of this form 10 feet high only draws 9 inches of water, thus leaving nearly the

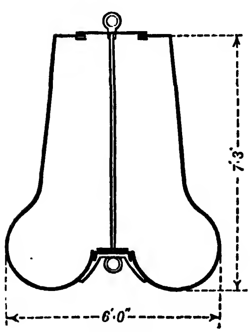


FIG. 38.

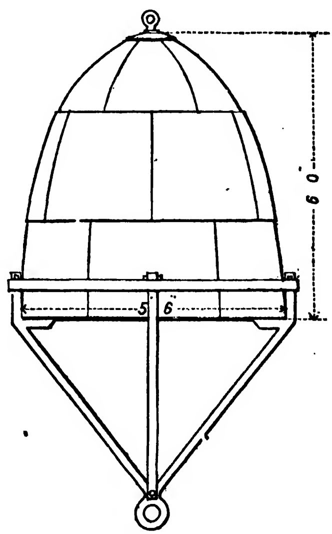


FIG. 39.

whole of the structure above the water, and the buoy always maintains a vertical position. The buoy shown in Fig. 39 has plates of the following thickness: the side plates are $\frac{1}{8}$ inch;

crown plate, $\frac{1}{4}$ inch; bottom plate, $\frac{3}{16}$ inch; hoop, $2\frac{1}{4}$ inches by $\frac{7}{8}$ inch; legs, 2 inches diameter; mooring-ring, 4-inch eye and $2\frac{1}{2}$ inches diameter; eye of top ring, 2 inches by $1\frac{1}{4}$ inch diameter. The weight of the buoy, 6 feet high and 5 feet 6 inches diameter, is 8 cwt. 1 qr. 13 lbs.; and of the hoop and legs, 3 cwt. 3 qr. 15 lbs.; and the cost, £21 7*s.* 6*d.*

Special-shaped buoys are made for marking the entrance to channels; of these an example of a pillar buoy is given in Fig.

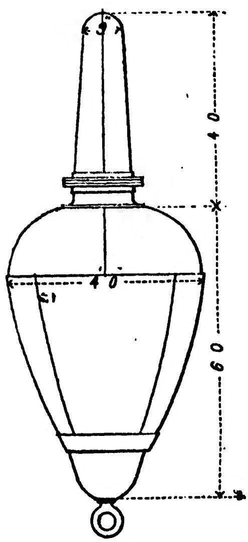


FIG. 40.

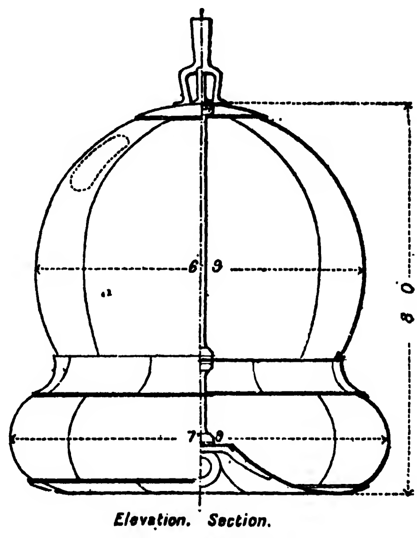


FIG. 41.

40. The spherical buoy used by the Trinity House is shown in Fig. 41.

For marking any dangerous shoals or the junction of channels bell buoys are frequently used, the noise from these being heard in foggy weather when the buoy is invisible. The bell is attached to the top of a spherical buoy, four clappers being so hung to a frame that with the slightest roll of the buoy one of them is certain to hit the bell. The illustration in Fig. 42 is from a design of buoy 10 feet in diameter, used by the Trinity House. The upper frame is made of wrought-iron tubes 4 inches diameter by $\frac{3}{8}$ inch thick; a 7-inch plate is secured to each leg and provided with indiarubber buffer for the clapper to strike against. The clappers are of wrought-iron, the ball

weighing 14 lbs., turned and forged to the end of a rod $1\frac{1}{8}$ inch diameter. The forked ends of the clappers are forged with solid steel eyes. The clapper has two points of suspension, and therefore acts without guides. A full-sized bell buoy weighs about 65 cwt., and costs £150. It requires an inch chain and 24-cwt. sinker to hold it in place, if there is much run of tide.

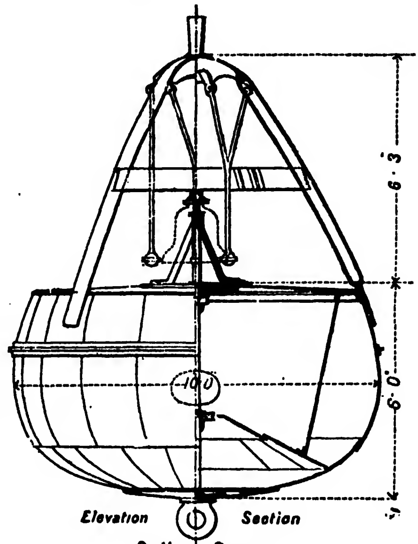


Fig. 42.

Buoys require cleaning and painting at least once a year, and in some situations more frequently. Tar withstands the corrosive action of the salt water better than paint, and this may be used for the black buoys, and for the bottom of the painted buoys up to the water-line. For those marked in colours, the special paints made by the Silicate Paint Company or the Torbay Paint Company resist the action of the salt water better than the ordinary paint having lead for a basis. These buoys should be galvanized.

The paint on iron buoys is apt very soon to become dirty, especially where white is used, from the rust. To prevent this, a wash of Portland cement applied to the buoy after the rust has been scraped off will be found not only a preservative to the plates, but assist in keeping the paint clean. On a tarred buoy a dusting of cement while the first coat of tar is wet will be found also to harden the surface and prevent rusting.

Buoys are moored by chains held in place either by sinkers or mushroom anchors. The length of chain allowed may be taken generally as from two to three times the depth of the water at high water in which the buoy is moored. With plenty of chain the buoy is less subject to sudden jerks in rough weather. If the chain is too short, not only is a greater strain thrown on the buoy, but it is apt to drag its moorings and become displaced. The 10-feet buoys require, in exposed situa-

tions, a 1-inch chain, the links of which are 6 inches × $3\frac{1}{2}$ inches, proved to a strain of $1\frac{2}{?}$ tons. For the next-sized buoys $\frac{7}{8}$-inch chains may be used, having links $5\frac{1}{4}$ inches × 3·15 inches, proved to a strain of 7 tons. For the second-class buoys, 6 feet to 8 feet high, $\frac{5}{8}$-inch chain is sufficient, with links 3·75 inches × 2·25 inches, proved to a strain of $4\frac{1}{2}$ tons; and for small 4-feet buoys, $\frac{1}{2}$-inch chain with 3 inches × 1·8-inch links, proved to a strain of 3 tons. Where the buoy and chain lies dry at low water, 6 fathoms of chain is sufficient. The weight of the 1-inch chain is 54 lbs. per fathom; of the $\frac{7}{8}$-inch, 40 lbs.; $\frac{5}{8}$-inch, 21 lbs.; and $\frac{1}{2}$-inch, 14 lbs.

Chains are made of three qualities, known respectively as BBB, BB, and B. The first is used for all the best class of shipping, and by the Trinity House for their buoys and light-ships. For buoys in rivers and estuaries the BB quality is sufficiently good, and costs 10 to 20 per cent. less than the best quality. The strains given above are for the second quality. The price of chain varies with that of iron, but it may be taken at from 15*s.* to 20*s.* per cwt., according to the size, for the BB quality.

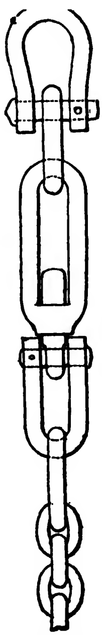


FIG. 43.

The chains are furnished at the end next the buoy with swivels, to allow of the free play of the buoy without twisting the chain, the swivels being coupled to the ring of the buoy by shackles; similar shackles are also used for attaching the chains to the rings of the sinkers. An example of a swivel is shown in Fig. 43. The metal is $\frac{1}{8}$ inch to $\frac{1}{4}$ inch thicker than the chains to which they are attached. The weight of shackles for 1-inch and $\frac{7}{8}$-inch chain is 28 lbs., and for $\frac{3}{4}$-inch and $\frac{5}{8}$-inch 13 lbs., and for $\frac{1}{2}$-inch chain 9 lbs. Buoy shackles are made with the eye swollen out, as shown by the top shackle in Fig. 43; this allows the buoy freer movement, and causes less wear. In this example, the bolt of the shackle is retained in its place where it passes through the shank by an oak pin. Smaller shackles are made with screw pins. For 10-feet buoys moored with 1-inch or $\frac{7}{8}$-inch chain, a shackle $1\frac{1}{4}$ inch thick, 10 inches long, 4 inches wide inside at the top, and $3\frac{1}{4}$ inches at the bolt, which is $1\frac{1}{2}$ inch by $1\frac{1}{8}$ inch, weighs 11 lbs. For the second-sized buoys moored with $\frac{3}{4}$-inch or $\frac{5}{8}$-inch chain, a shackle 1 inch thick,

$8\frac{1}{2}$ inches long, $3\frac{1}{2}$ inches and 3 inches wide, with bolt $1\frac{3}{8}$ inch by $\frac{7}{8}$ inch, weighs 7 lbs.

For coupling the chains, screw shackles with straight sides (Fig. 44) weigh for 1 inch thick 3 lbs., and for $\frac{3}{4}$ inch thick 2 lbs. For small buoys using $\frac{1}{2}$-inch chain, shackles $\frac{7}{8}$ inch thick, 7 inches long, 3 inches and $2\frac{1}{2}$ inches wide, with $\frac{7}{8}$-inch screw bolt, weigh $3\frac{1}{2}$ lbs. The swivels weigh respectively, for first size, $1\frac{3}{8}$ inch thick, 28 lbs.; second size, 13 lbs.; small size, 9 lbs. The Trinity House buoys are held in position by cast-iron sinkers (Fig. 45).

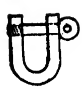


Fig. 44.

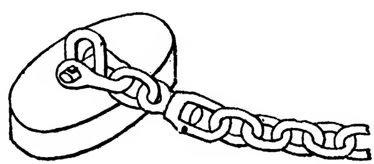


Fig. 45.

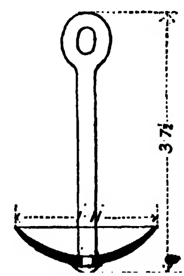


Fig. 46.

These weigh from 14 to 16 cwt. for the 8-feet and 10-feet buoys. The mushroom anchor, shown in Fig. 46, is a very effective mooring, and rarely drags. The mushroom part is of cast iron, and the shank of wrought iron. The large size, 2 feet in diameter, with $2\frac{3}{4}$-inch shank, 3 feet 6 inches long, and $3\frac{1}{2}$-inch eyebolt, metal in thickest part $1\frac{3}{4}$ inch, weighs $1\frac{3}{4}$ cwt.; the second size, 1 foot 6 inches in diameter, with 2-inch shank, weighs $1\frac{1}{4}$ cwt.; and the third size, 14 inches, with $1\frac{3}{4}$-inch shank, weighs $\frac{3}{4}$ cwt. A buoy when properly moored seldom breaks adrift. The greatest danger arises from ice, when large drifts are sent out of the rivers at the breaking up of a long and hard frost.

For lighting the channel leading to New York harbour, between Sandy Hook and Coney Island, a system of electric buoys has been adopted. The buoys, made of wood 50 feet long and 15 inches diameter, are shackled to a cast-iron sinker weighing 2 tons. A cable from the shore is led up to an electric light on the top of each of the buoys, the power being supplied from one station at Sandy Hook.

Mooring Buoys.—In Fig. 47 is given an illustration of a wrought-iron floating mooring buoy for fixing in a tidal channel.

The plates are $\frac{3}{8}$ inch thick, single riveted, with $1\frac{1}{2}$-inch overlap, the rivets having $2\frac{1}{4}$-inch pitch. The man-hole is fastened to the plate with $\frac{3}{4}$-inch bolts, bedded on with red lead. The spindle or centre bar is 3 inches diameter, passing through the

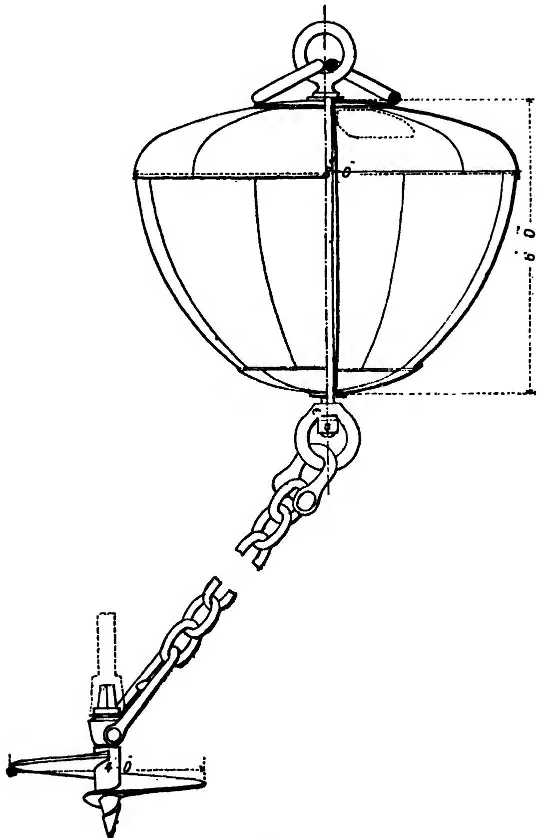


FIG. 47.

buoy in a tube, so that the buoy can revolve round the spindle. There are two 3-inch wrought-iron mooring rings 1 foot 3 inches diameter. The chain has $2\frac{1}{4}$-inch stud link. This buoy weighs 3 tons.

The mooring to which the buoy is attached consists of cast-iron screw having flanges 4 feet in diameter, 9-inch pitch, with shaft 5 inches in diameter, and 3-inch wrought-iron shackle, with 4-inch bolt. The weight is about $21\frac{1}{2}$ cwt. The screw is screwed into the bed of the channel from 8 feet to 10 feet

deep, where the soil is fairly good holding ground. In soft and yielding soil it may be necessary to go down 15 feet to 20 feet. The screws are screwed down with the mooring-chain attached by means of a wrought-iron shaft, having a socket at the bottom fitting on to the square head of the screw, and keyed at the top to a capstan, fixed upon a platform, laid upon two barges placed side by side. The shaft is made in lengths of 10 feet, connected by key joints.

Lighting.—There are three systems in use for intensifying the lights of the lamps used in floating or fixed beacons. By the catoptric system the light is reflected by a silvered copper parabolic reflector, by means of which the beams of light are brought into parallel rays sent in the direction desired. By the dioptric system the diverging rays of light are bent in the direction required by refraction, the flame being placed in the focus of a glass lens, by means of which the diverging rays are bent parallel to each other so as to form one solid beam of light, as shown in the diagram (Fig. 48). The third, or catadioptric, consists of a combination of the other two.

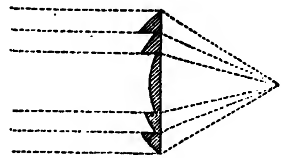


FIG. 48.

Lights are classified by orders, depending on the height and diameter of the apparatus. The first three orders are used for sea or coast lights. The fourth order is the largest used for harbour lights, and has an internal radius or focal distance of 9·84 inches, making the diameter of the apparatus 19·68 inches, the height of glass being 29·11 inches (the original figures are metric); the fifth order has a diameter of 14·76 inches, and a height of 21·83 inches; the sixth a diameter of 11·87 inches, and a height of 17·46 inches. For smaller lights than these, the glass for the lens is made in one piece. For harbour lights, where it is not necessary to show the light all round the horizon, a dioptric lens covering only the part which is required to be lighted is used, having a parabolic plated reflector at the back; this arrangement gives a greater vertical divergence to the rays, which enables the lights to be kept in sight when approaching near to them, a necessity where the lights are used as leading lights.

For the fourth order a two-wicked burner $\frac{3}{16}$ inch diameter is used, and for the other orders a single wick, which consumes about three-quarters of a pint of oil per night.

A red tinge is given, when necessary to avoid confusion, by the use of a coloured chimney to the lamp, or by allowing the light to pass through a sheet of coloured glass. A red light can only be seen at about half the distance of a white light, the proportion, found by practical experiment by Professor Tyndall, being as 21 is to 9. Green colour absorbs even a larger proportion of the light, and lanterns showing this colour are only suitable as distinguishing marks on pier-heads, bridges, or similar situations.

From tests as to the visibility of white, red, and green lights, made at the Long Beach light-station, near New York, by the United States Lighthouse Board, to determine the respective values of these colours for ship's lights, it was found that on a clear night, at a distance of one mile, the white light with one candle-power was clearly visible; the red light was barely visible with 2·20 candle-power; and the green light with 2·10 was very faint. At two miles the red light was barely visible with 5·75 candle-power, and the green could only be seen indistinctly with 10·50; and it required a candle-power of 29 to make the red and green lights visible at this distance, while 3 was sufficient for the white light. At four miles the red with 34, the green with 42, and the white with 10, were invisible to the naked eye. At five miles the white with 29 was faintly visible, and with 33 clearly visible. On a cloudy night at one mile, the red light at 1·45 candle-power was indistinctly visible, while the green light required 2·10 candle-power to become faintly visible, and the white light required only 1·04 candle-power to be seen satisfactorily. At two miles the red light was barely discernible at 5·75, and the green light indistinctly visible at 10·50, and 42·40 was the least power for a clear colour. The red light was distinct at two miles at a candle-power of 23·60; the white light at three miles distinct at 3·20, at four miles with 5·60, and five miles 17·50. As a result of the trials, it was recommended that a white light of one candle-power could be used for one mile distances; 2 candle-power for two miles; 30 candle-power for five miles. For the red and green light, 4 candle-power should be used for one mile, 40 for two miles.

The height a light should be placed above the level of the sea to be seen at a given number of miles, may be found by the following formula:—

$$\frac{\text{Miles}^2 \times 4}{7} = \text{height in feet.}$$

Thus if the distance required be 10 miles—

$$\frac{10^2 \times 4}{7} = 57{\cdot}14 \text{ feet.}$$

Beacon lights on the coast were formerly supplied by the burning of wood and coal in iron grates. At the present time, oil, gas, and the electric light supply the light. The first floating light was supplied with candles in a glass lantern suspended from the yards of a vessel moored in the Nore in 1732. The candles were subsequently superseded by lamps burning fish oil, the lanterns being hung from the yards. Mr. Robert Stevenson, at the beginning of the present century, adopted the plan now generally in use, of a lantern surrounding the mast, which can be raised or lowered for cleaning and trimming. This was further improved by the use of the catoptric system, and by hanging each lantern and reflector on gimbals. The flat wick burner gave way to the Argand, which has been further improved. The burner invented by Sir James Douglas consists of three or more concentric wicks, increasing the intensity of the light from 500 to 5000 candle-power. The lights on the new Eddystone Lighthouse are equal to 160,000 candle-power.

Sperm oil, which was formerly used, was superseded by colza oil, and this has given place to mineral oil. Colza oil is considered more safe than mineral oil, but it is double the price, and requires greater heat to produce the vapour, and is more difficult of application, as it must be forced up to the burning point, so that it may just flow over the edge of the burner, a necessity not required with mineral oil, which will flow up the wick in sufficient quantity by capillary action alone, except in the lights of high power. Mineral oil gives a more brilliant light than vegetable, and does not congeal except at a very low temperature. Lamps using the best kind of mineral oil will burn for a very long time without the wicks being cut or trimmed, and, in fact, not requiring any other attention than the lighting and putting out. Lamps constructed on the Argand principle range up to 2000 unassisted candle-power. The more powerful lights have as many as ten concentric wicks, the oil being maintained at a constant level of from two to three inches below the flame. The structure and material of the wick and the adjusting mechanism

is so perfectly adapted to the oil that these lights will go on burning for five hundred hours without trimming.

The lights used in estuaries and tidal rivers consist of floating lights for marking the course of the navigation; beacon lights for marking prominent points; and leading lights for marking the entrance to rivers, or the course along the reaches of confined and winding channels. The vessels used for floating lights being in sheltered positions, are of a smaller character than those used for sea lights.

The "Bar Flat Light," maintained by the Corporation of Lynn at the upper end of Lynn Deeps, to denote the entrance to the Lynn and Wisbech channels, may be taken as an example of an estuary light maintained by a local authority. This is an iron vessel, 74 feet long by 19 feet beam, and drawing 8 feet of water, and has ample accommodation for the crew. The light is provided by three Argand lamps burning in a lantern surrounding the mast, and provided with dioptric lenses protected by plate glass. The light is visible at a distance of eight miles. The lamps are hung on gimbals, and the lanterns can be lowered for cleaning and trimming. The lamps burn crystal oil, which costs about £12 a year. A gong is provided for signalling in foggy weather. The crew consists of captain, mate, and two hands; the captain, or mate, and two hands being always on board, and the relief men employed at the buoy yard when in harbour. The cost of the vessel was £2500, and of the light £265. The annual cost of wages and maintenance is about £560, and the charge for interest and repayment of loan £140, making the total cost £700 a year. The cost of maintenance is met by a toll of a halfpenny per ton register on all vessels passing or using the light, which the Corporation are authorized to take under an order of council.

Lightships in English waters are always painted red, and carry a ball at the masthead. Small lightships are moored by a bridle having 1½-inch chain attached to a mushroom anchor weighing about 30 cwt.

In channels leading to small harbours the navigation is much facilitated if a floating light can be provided to mark the way during the dark tides in winter, say from September to March. For such positions, if well sheltered, a small boat of about twenty tons, having a crew of one man and a boy, is sufficient for the purpose. The crew can be relieved once a fortnight from the men employed in the harbour. A floating light of this description

has been used by the author in the channel leading from Lynn Well to Boston Deeps, enabling the continental steamers and steam fishing-trawlers to navigate the channel and reach Boston dock at the night tides, which otherwise they would have been unable to do.

The light consists of a lamp having a Hincks $1\frac{1}{2}$-inch duplex burner protected by a glass chimney. The lamp is enclosed in a copper lantern, having a circular dioptric lens 12 inches in diameter and 12 inches high. The lamp burns two pints of mineral (crystal) oil in a winter's night, and is visible in ordinary weather at eight miles' distance. The light is visible on all sides. The lantern is suspended on gimbals in an iron frame, which slides on an iron rod supported by a light wrought-iron skeleton tower 35 feet high, and lowers into a wooden hut at the bottom for lighting and cleaning. A small masthead light is also hung aft. This light is fixed on an old schooner purchased for the purpose. The cost of a suitable iron vessel would be about £400. The main light and lantern cost £15; the smaller riding light, 25*s.* By this arrangement a single lantern is sufficient as against the three required where the light is arranged round the mast. The annual cost of this light-vessel is as follows:—

Wages, including relief men for thirty weeks, £55; fifty gallons of oil, including that used in the cabin, £1 15*s.* 5*d.*; coal, £5; or say £62 for the seven months, September to March.

The boat carrying the light rides in two fathoms at low water, and $5\frac{1}{2}$ at high water, and swings with the tide, being moored in a bridle. The ground chain is $\frac{7}{8}$ inch thick, 120 fathoms long, moored at each end by a mushroom anchor; from the centre of the ground chain a length of ten fathoms goes to the vessel. By this arrangement the short length of the veering chain requires a less distance for the vessel to swing in than if it were moored to a single anchor—a great advantage in a narrow channel.

In foggy weather, bells, gongs, or fog-horns are used on board lightships to indicate their position. The bells and gongs are hung on deck, but so arranged that the man sounding them can remain below under shelter. In the large stations on the coast the fog-horns and syrens are worked by gas-engines, and can be heard at very long distances. For lightships in protected estuaries a small-class fog-horn is made, worked by hand. Hansen's

Norwegian fog-horn is useful for this purpose, and costs only £2 10*s*.

The "Sirenette," supplied by the Pulsometer Engineering Company, is adapted for use on light-vessels and in situations where only hand-power is available. The machine consists of an air-cylinder, pump, and syren, and requires two men to work it. The sound can be heard in foggy weather at a distance of from two to three miles; the price is £100. A larger machine, consisting of a caloric engine air-receiver, and automatic sounding-gear and syren, costs £250.

Beacon Lights—In rivers having straight reaches, like the Clyde and the Tees, the channel is marked by fixed lights on the top of stone beacons. These lights are now supplied by compressed gas, and consequently do not require daily attention. On the Thames Sir James Douglas has adopted wrought-iron framing for two lighthouses erected in 1885, one at Broadness, near Grays, and the other at Stoneness, opposite Greenhithe. The light at Broadness is provided by compressed gas, supplied from the works belonging to the Trinity House at Blackwall. The gas is stored in two steel gasholders, having a collective capacity of 280 cubic feet. The consumption of gas is at the rate of 2·2 cubic feet per hour. The intensity of the light is equal to 50 candles. The holder will keep the light burning for 636 hours. The light flashes at intervals of ten seconds, the apparatus for producing the flashes being moved by clockwork. The cost of the house and light complete was £945, and the annual cost of maintenance £124. The light at Stoneness is produced by the combustion of spirit of petroleum. The spirit is stored in a cistern in the building, capable of holding a fortnight's supply, and flows to the lamp by gravitation. The spirit is vaporized by the heat of the light, and continues burning without attention as long as the supply lasts, and its use is therefore adapted to cases of single or isolated lights, where the production and conveyance of compressed gas is not practicable. The main objection to this form of light is the great danger arising from the low temperature at which the petroleum vaporizes, being only a little above that of the atmosphere in summer. The intensity of the light is about sixteen candles, increased by a dioptric lens to sixty candles. The cost of the structure and light was £711, and the annual cost of maintenance £92. A more detailed description of these lights

and a drawing of the structure will be found in the paper by Mr. Ayres in the ninety-third volume of *Proceedings of the Institution of Civil Engineers.*

The light adopted at Stoneness is known as the Lindberg system, having been invented by Herr Lindberg, an engineer of the Swedish Lighthouse Board, whose patent rights are represented in this country by Messrs. J. Trotter & Co., of London. By aid of this apparatus an occulting light can be provided without the use of clockwork, and a light sustained for several days without the cost of making and conveying compressed gas. For an occulting light, the revolutions are caused by the heat from the lamp, and, therefore, as long as the lamp keeps burning the apparatus will revolve. The illuminating medium is lythene oil, which costs 1*s.* 9*d.* a gallon, for which a specially constructed burner is used; or when this oil cannot be obtained, or when a stronger light is required than the burners give, a burner to consume ordinary paraffin oil can be used, which will burn for a week without attention. These lights, as used in Sweden for beacon lights, are placed in wooden towers, which cost about £45; the cost of the apparatus for a sixth-order revolving light and fixing being about £100.

Leading Lights.—The approach to a channel is frequently marked by two lights, which, when in a line, lead direct to the entrance; and the same plan is used for facilitating the navigation of winding reaches of river channels. For river work these lights may be placed about 20 chains apart, and the back light should be at least 10 feet above the other.

Fig. 49 shows an economical form of lighthouse, designed and used by the author for this purpose. The light is supplied by a circular burner of the Defries pattern, having a wick 3 inches in circumference enclosed in a glass chimney. The lantern has a semicircular dioptric lens 18 inches high by 10½ inches wide in front, and parabolic silvered copper reflector at the back, and is suspended from a bracket projecting from two uprights attached to the house, and kept in place by guiding-rods. The lamp consumes less than a pint of mineral—crystal oil—in a long winter's night, and is visible in ordinary weather at a distance of five miles. The lantern lowers on to a table by means of a small winch and chain, and can then be drawn into the house through a shutter for trimming and lighting. The lantern remains in the house when not in use. The oil for filling the

lamps is contained in a galvanized iron drum holding twenty gallons, and so hung on a cast-iron frame that it always assumes a vertical position, the tap being at the top. When oil is required the drum is drawn forward, and the lamp filled from the tap. The position of the tap provides against all risk of leakage and waste. The framework of the house is of fir, and the sides and roof are covered with galvanized iron. The cost is as follows:—

	£	s.	d.
House fixed complete	10	0	0
Lantern, made of block tin, dioptric lamp, and reflector ...	10	0	0
Winch	1	0	0
Oil drum and stand	2	0	0
	£23	0	0

The chief cost of maintenance is in the labour for lighting. An old pensioner is generally put to the work at a cost of 10s. a week, his range extending over, say, three miles of river, and having six lamps under his charge. The annual cost under these circumstances would be under £5 per lamp for labour and oil, the lamps being lighted for seven months in the year.

Gas-buoys.—The application of compressed oil gas to the illumination of beacons and buoys has added a very valuable adjunct to the navigation of rivers and estuaries during dark tides. By its use for lighting fixed beacons many of these can now be lighted which otherwise could not have been done, owing to the expense incurred in providing accommodation for and maintaining the necessary staff. The gas used for this purpose is that made under the patents held by Pintsch's Patent Lighting Company. It is made from paraffin once refined. The oil is vaporized and gasified in iron retorts, and after cooling and purifying is carried to a small gasometer. The whole apparatus is contained in a space of about 40 feet by 16 feet (Fig. 50).

From the gasometer it is drawn by a pump and forced into cylindrical holders having a cubic space of 370 feet, containing 3700 cubic feet of gas, at a pressure of 150 lbs. to the square inch. These holders are conveyed to the buoys, or the holders of the fixed lights, in a boat, and the gas is transferred to the receiver of the buoy by a pipe connection having a stop valve. The gas is conveyed into the buoy at a pressure of 90 lbs., and

the quantity of gas so passed into the buoy is sufficient at this

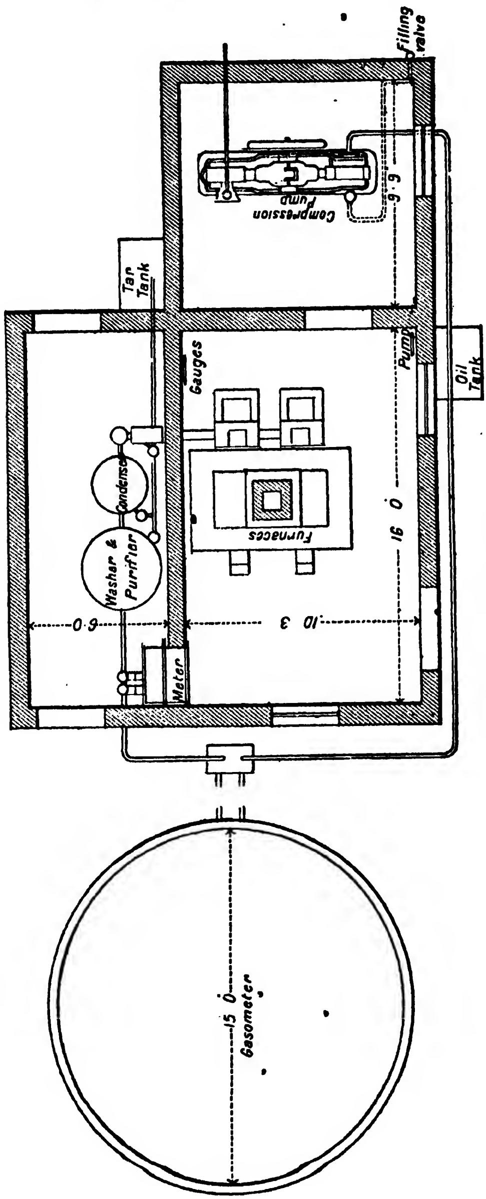


FIG. 50.—Oil gas-works.

pressure to keep it burning day and night for two months,

or longer according to the size of the receiver. Two store cylinders of the above dimensions are sufficient to charge three buoys.

The consumption of gas in the buoys is at the rate of 0·8 cubic foot per hour, and each light consumes about 9000 cubic feet a year.

The emission of the gas is retarded at the burning point by an automatic regulator, which allows it to flow at a pressure equal to $\frac{5}{10}$ inch water-column. Provision is also made to meet the sudden extinguishing of the light by means of a blow from a vessel or mass of wreck. The flame is protected by a specially designed lantern having a dioptric lens. The cost of making the gas varies with the price of oil from 8*s.* to 11*s.* per thousand cubic feet. By the aid of the dioptric lens, the illuminating power is made equal to thirty-five candles. The light is placed 12 feet above the water, and is visible at a distance of three to five miles. Coal-gas loses a large proportion of its illuminating power by compression, and is therefore not suitable for the purpose.

The cost of installation of the gas plant and buildings is about £450. A transport holder, 27 feet 3 inches by 4 feet 3 inches, capable of filling two lights, costs £160. The cost of a gas-buoy 10 feet in height is £350 to £400. Cylinders, 17 feet 6 inches by 4 feet 2 inches, with lanterns and apparatus for fixed lights, cost £185, or if with occulting light, £200. The buoys are moored with $1\frac{1}{4}$ inch chains to mushroom anchors, 4 feet in diameter, weighing about 30 cwt.

In 1881 the Clyde Lighthouse Trustees commenced lighting with gas buoys, and by 1883 several beacons, including the Gantock Beacon, were established, a sketch of which is given in Fig. 51. Subsequently the lighthouses at Cardross and Dumbuck were also lighted by compressed oil-gas. The Garmoyle lightship has been converted into a gas light-boat, and the expense of the crew saved, the light burning six weeks without attention. The Clyde Trustees have nine buoys, placed about half a mile apart, between Port Glasgow and the month of the Leven. The gas is supplied to these buoys from the works of the Clyde Lighthouse Trustees at Port Glasgow, and is put into the buoys at a charge of 21*s.* per thousand cubic feet. The cost for one year for repairs and gas is about £14 for each buoy.

On the Tees there are two 9-feet buoys and three beacons

lighted by compressed gas. The buoys hold sufficient for six weeks, burning night and day. The cost, including the plant for making the gas, has been about £3400, and the working expenses per light are £21 a year, including oil, coal, stores, and repairs. Since the channel has been well lighted the number of ships navigating is nearly as great during the dark tides as in the daytime.

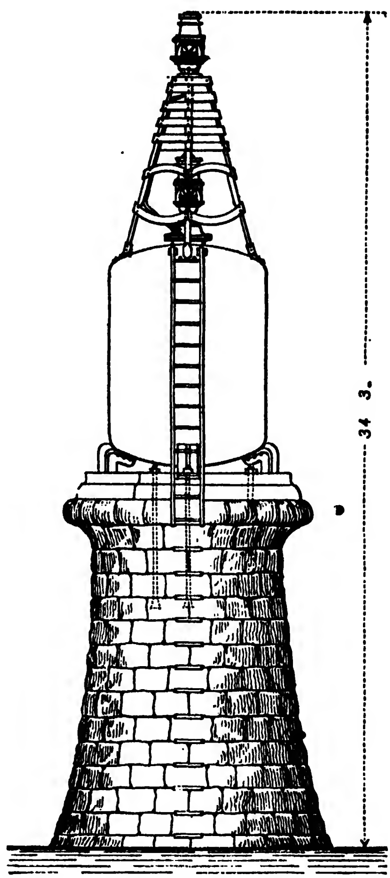


Fig. 51.—Gas-beacon.

There are two gas-buoys in the estuary of the Ribble and one in the Irish Sea, marking the entrance to this river. This buoy shows an occulting light of four seconds' duration of flash and two seconds' interval, visible for eight miles. In addition to distinguishing the entrance to the Ribble, it is of service to the general coasting trade. These buoys are also in use on the Thames, where there are fifteen lights; the Mersey; in the channel to Lynn; the St. Lawrence in Canada, where there are nine buoys; on the Elbe, the Scheldt, the Danube; on the Suez Canal, where there are one hundred buoys and beacons lighted by compressed gas; also at Naples, Melbourne, Havre, Oporto, and St. Petersburg.

Fig. 52 gives an illustration of a small floating light on this system, as used at Barrow-in-Furness.

The gas-buoys used by the Trinity House, shown in Fig. 53, are spherical in form, having a wrought-iron frame to carry the lantern. The weight of these is 80 cwt., including the frame, which is about 3¼ cwt. The capacity of the gas-holder is 382 cubic feet. The lighting apparatus consists of three fish-tail

burners, surrounded by a 4-inch dioptric lens. The initial intensity of the naked flame is seven candles, which is increased by the lens to thirty-five candles. The focal plane of the light is 12 feet above the surface of the water, and it can be seen

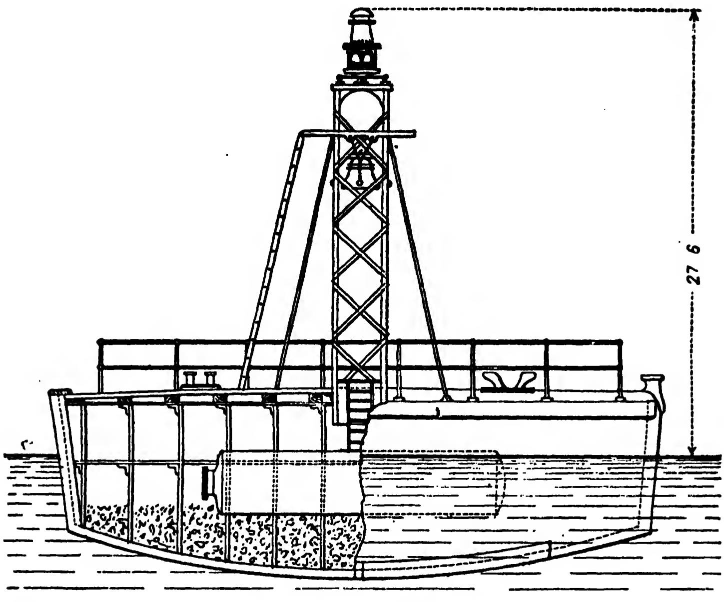


FIG. 52.—Floating gas-light.

at a distance of four to five miles. The cost of the buoy was £420.

Beacons are used for marking the boundary of the channel or line of navigable depth, when the sides are covered at high water, and also are fixed on sandbanks in an estuary, for the purpose of forming prominent marks for the use of fishermen, in which position they are also of use as refuges for men lost on the sands with a rising tide. For the smaller class of rivers poles 20 feet to 30 feet long are placed on the banks, having a triangle or other shaped frame at the top, and painted white, or black and white. Where there is much run of tide they are secured by a ½-inch chain round the bottom of the pole, and attached to a stone sunk in the bank. On first-class tidal rivers the channel is marked by structures composed of stone or concrete, which, as already mentioned, are provided with lights. Beacons placed on

sands in an estuary consist of a pole about 35 feet long let into a ludget buried in the sand, and held in position by stays made of wrought-iron rods $\frac{7}{8}$ inch thick, tightened up by screws and attached to cast-iron screw-pile moorings (Fig. 54). On the top is a beacon consisting of a triangle, drum, or other distinguishing form, and a platform of sufficient size for one or two

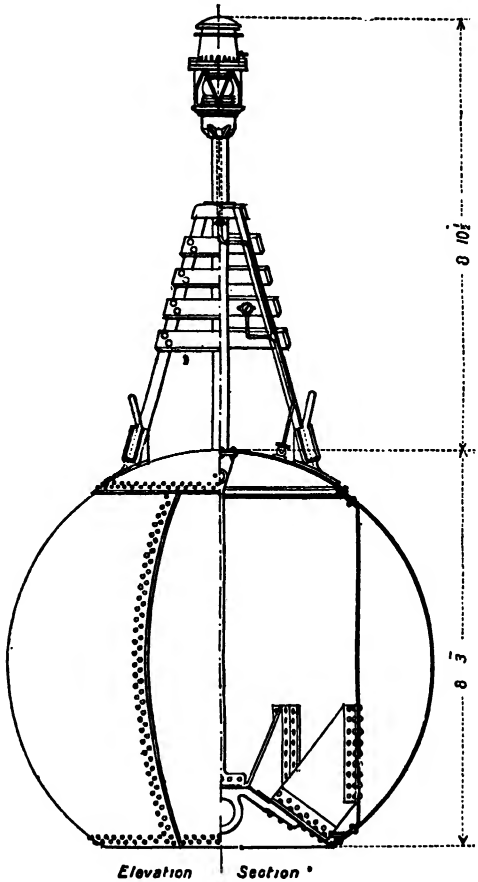


Fig. 53.—Gas-buoy.

men to rest on. Cleats are fastened to the pole to enable them to reach the top. The chains and ironwork should be galvanized to resist the action of the salt water. The drum shown in the illustration consists of two wrought-iron hoops attached to central collars, and having iron bars $\frac{3}{16}$ inch by $1\frac{1}{4}$ inch, spaced

3 inches apart. A hole is left at the bottom of the drum of sufficient size for a man to get through, the refuge in this case

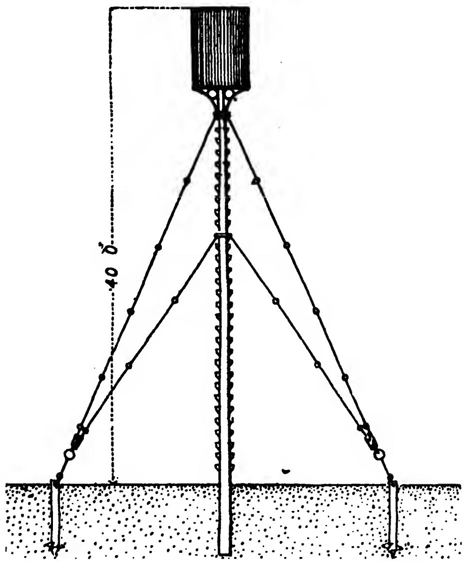


FIG. 54.—Beacon.

being made inside the drum. The cost of a beacon of this description is about £20.

"Lighthouses," by Stevenson (Weale's series); "Our Sea Marks," by E. Price Edwards (London: 1884); *The Engineer*, March 29, 1889, paper by Mr. James Douglas on "Lighthouses and Lightships;" *Min. Proc. Inst. C.E.*, vol. lvii., "The Electric Light as applied to Lighthouse Illumination," by James Douglas.

CHAPTER XIII.

SURVEYING TIDAL RIVERS AND ESTUARIES.

An accurate knowledge of the physical conditions of a tidal river and its estuary, and also the tides and currents, is absolutely essential preparatory to any works being undertaken for its alteration or improvement.

It is unnecessary here to deal with the ordinary methods of surveying, but there are certain terms, rules, and appliances used in making hydrographic surveys, and for obtaining information as to the tides and set of the currents, which it is proposed shortly to describe.

Hydrographic Terms and Measures.—In dealing with a river it is always understood that the right-hand bank is that which is on the observer's right-hand side when going down the river from the source to the sea. In a tidal estuary the opposite rule has been adopted, and the right-hand or starboard side of the channel is that which lies to the right hand of the mariner on entering the channel from the sea and going up.

Low water in an estuary or tidal river is always taken to mean the level of the water at low water of ordinary spring tides, and high water that of high water at the same period, the terms being abbreviated on charts by the letters L.W.S.T., H.W.S.T.; for equinoctial tides, E.H.W.S.T.; for unusual tides, Ex. H.W.S.T.; and for neap tides, H.W.N.T. or L.W.N.T. The terms, *the rise and range of the tide, mean and half-tide level, flood,* and *ebb* have been already explained in the chapter on "Tides."

The lineal measure used on all marine charts is the *nautical* mile, or the sixtieth part of a degree of latitude, equal to 69·121 statute miles, or by the Admiralty knot, 69·0909 statute miles. The precise length of a degree has undergone modification from time to time as astronomical observations have become more

perfect. It is generally accepted now as being 6082·66 feet, being equal to 1·152 statute mile. The length of the nautical mile adopted by the Admiralty is 6080 feet, equal to 1·515 statute mile. For convenience the nautical mile is generally taken by mariners as 6000 feet, and the degree as 69 statute miles.

A knot is the same length as a nautical mile, and is the term used in describing the speed of a ship, being one nautical mile passed over in one hour. When, then, the expression is used that a vessel makes ten knots, it means that this distance is covered in an hour, and the last two words in the expression often used, of "knots *per hour*," is an unnecessary repetition. A nautical mile is divided into ten parts called *cables*, and distances are expressed in miles and halves or quarters, or cables. Thus five miles and a quarter, or 5 miles 3 cables, would be written $5\frac{1}{4}$ and $5\frac{3}{10}$ respectively. The vertical measures of the depth of the water in estuaries or the sea is generally expressed in *fathoms*. An English fathom is 6 feet. The length of the fathom in other countries will be found in Appendix III. One hundred fathoms is taken as equal to one cable, and 1000 fathoms as a nautical mile.

Charts.—There are certain standard abbreviations used in all marine charts to denote the conditions of the tide; the physical characteristics of the estuary; the nature of the material of the bottom, the shore, or the coast; the description of buoys and sea-marks, etc. A schedule of these will be found in Appendix IV.

The charts prepared by the hydrographic department of the Admiralty, and issued for the use of mariners, are to be obtained at small cost. Each of these charts covers a certain length or department of the coast, the principal estuaries and ports being also given on an enlarged scale.

Index charts, showing the coast or estuary in any part of the world covered by any particular chart, are also issued. These are convenient for ascertaining the particular chart required.

The charts relating to harbours and estuaries are generally drawn to a scale of one or two nautical miles to an inch, being the natural scales of $\frac{1}{72960}$ or $\frac{1}{145920}$. They show the coast-line and prominent objects on shore, the shore, the space covered by water at low water of ordinary spring tides, the depth of water in the channels, and the height of the sands above low water. The depth of water is given in fathoms, except on the

estuary and harbour charts, where it is generally in feet. The height of the sands that are bare at low water is distinguished by the figures being underlined. A scale of nautical miles is placed on some charts; on others only the degrees of latitude and longitude. The distances on the chart may be scaled from the latitude. The degrees of longitude, if used, would require to be reduced by calculation for different latitudes, the length varying at all places between the poles and the equator.

In marine charts the bearings and direction of the plan are always magnetic. On plans of harbours and estuaries for engineering purposes, the drawing is always made to coincide with the true north.

The needle of the compass does not at the present time point to the true north. The number of degrees which it deviates from this vary with the meridian of the place, increasing westerly about 7 degrees between the east coast of England and the west coast of Ireland. The local variation is given for each place along the coast in the Admiralty Sailing Directions. About 300 years ago (1657–62) there was no variation. After that it began to move westerly, and attained the greatest variation at 24° 27′ west in 1818. After which the variation began to move easterly again, and at the present time at the meridian of Greenwich it is 17° 12′ west. The rate of decrease has not been regular. Between 1830–40, it was at the rate of 3′·9; 1840–50, 5′·9; 1850–60, 6′·9; 1860–70, 7′·1; 1870–80, 8′·2; the present rate is 8′ a year. Besides the local and annual variation, there is also a diurnal change, the needle moving westerly in the morning and until an hour after noon, and then going easterly, the maximum variation being 12′, the mean being at 10 a.m and 7 p.m. The amount of variation differs slightly at different periods of the year.

Nautical men use the points of the compass to express the bearing of a channel or of any object, the magnetic north point being the datum, and the angle the object makes to this being expressed by the points of deviation from the four cardinal points. Engineers express the angle by the number of degrees, minutes, and seconds into which the circle is divided. There are 32 points to the compass, the divisions between these being expressed by quarters.

There is no fixed system for expressing the divisions, but they are read from the north to the east, and thence by south

to west, in the same direction as the hands of a watch travel. This rule is sometimes departed from for the sake of brevity and clearness. Thus N.N.W. ½ W., is preferable to N.W. by N. ½ N., but E. by N. ½ E., instead of E. ½ N., would be utterly wrong.

A point is 11° 15′, north being 0.

The 32 points of the compass and the corresponding angles will be found in the Appendix.

The degrees of longitude on the English Admiralty charts are reckoned east or west of the meridian of Greenwich. The charts of Russia, Sweden, Norway, Denmark, Holland, Austria, and the United States use the meridian of Greenwich. France has adopted that of Paris, 2° 20′ 15″ east of Greenwich; Spain, that of San Fernando, Cadiz, 6° 12′ 24″ west of Greenwich; Portugal, that of Lisbon, 9° 7′ 32″ west of Greenwich.

Further particulars as to the physical characteristics of the coast, the nature of the bottom, set of the tides, etc., may be obtained from the books of Sailing Directions issued by the Admiralty, those for the South Coast being known as Parts 1 and 2 of the Channel Pilot, for the East Coast, Parts 1 to 4 of the North Sea Pilot; and for other parts of the kingdom, as the Sailing Directions for any particular coast.

The Admiralty charts are prepared for the use of mariners, and, although affording a large amount of valuable and useful information, are not sufficient for the purpose of an engineer. Unless a chart of the estuary on a large scale already exists which can be corrected and brought up to date, a fresh survey will be necessary.

In nearly all the important estuaries of this kingdom there exist marine surveys which were made by the late Mr. Giles for Mr. J. Rennie, Mr. J. Walker, and other engineers, early in the present century, when works on a very extensive scale were undertaken for the improvement of the ports and harbours of the kingdom. These charts are recognized as being very complete and accurate, and may be taken as a model for any similar work which an hydrographic surveyor has to perform.

Marine Surveying.—Captain Wharton, the Admiralty hydrographer, remarks in the Instructions to Surveyors that the formation of an accurate chart is the result of many operations, all demanding care, attention, and method. To ensure method and uniformity in preparing charts for the Admiralty, instruc-

tions are issued by the hydrographical department containing rules which have to be observed by all surveyors engaged in making marine surveys for this department. In making plans of estuaries for engineering works it is desirable, as far as possible, to observe the same rules. These rules, altered to suit an engineering survey, may be briefly described as follows: All charts and plans, when practicable, are to be constructed upon the true meridian; soundings to be reduced to mean low water of ordinary spring tides in feet and fractions of a foot; underlined figures to denote the height of the banks above low water; the direction and velocity of the tide to be expressed by arrows, $\rightarrow$ for the flood, and $\longrightarrow$ for the ebb current, and by knots and fractions of a knot; the period of the tide by the initials 1st Qr., 2nd Qr., etc.; the scale on which the plan is drawn to be always given; the natural proportion which the chart scale bears to the real dimensions to be represented thus: $\frac{1}{63360}$ for a scale of 1 inch to 1 statute mile; different types of lettering to be used for different classes of objects, the lettering of a modern published Admiralty chart to be taken as an example; names or remarks to have the same general direction, so as not to require the plan to be turned in different directions to read them. In colouring a plan water is always to be denoted by blue, the tint being made deeper according to the depth, and varied so as to show different depths, the main deep-water channels being shown by the darkest tint; sands and sandbanks to be yellow, shingle brown (burnt sienna), mud grey, marshes green.

The initials denoting the abbreviations to be used will be found in Appendix IV. Soundings to be placed in straight lines perpendicular to the coast. The level of low water adopted to be referred to a fixed datum given on the plan. This, in England, should invariably be the ordnance datum, or in other countries the standard datum of the country. The dimensions to be in statute miles, nautical miles being used on charts for marine purposes.

Plans should be mounted on holland or linen.

Surveying.—In making the survey of an estuary considerable experience is required. The work is more tedious and slow than on land, owing to the interference of the tides and the short time that the low-water channels are visible. The first and most important part of the work consists in laying out the base-line.

With regard to this, Captain Wharton considers that "the number of times a base must be measured depends on circumstances; that for a harbour plan twice will be sufficient if the measurements agree to a foot or two. If the survey is of great extent, three or four times will be more satisfactory."

The chief angles being set out by the theodolite, the box sextant will be found a very convenient instrument for filling in, especially in places where a theodolite could not be set up owing to the sand being quick or the mud soft. With a little practice angles can be taken with great accuracy with this instrument. Its accuracy can always be verified by completing the circle and by adding the degrees together, making the total up to 360. This instrument is also useful in determining the position of a buoy, beacon, or other similar object, from a single station. The observer having moored his boat to the buoy, an angle is taken to two other objects, the position of which is known and marked on the plan of the estuary. This angle being produced on a piece of tracing-paper, the paper is moved about until the two lines subtended by the angle exactly cover the two distant objects, the position of the buoy on the plan will then be at the vertex of the angle. If three or more objects are taken, it will check the accuracy of the observation.

The prismatic compass is frequently used for taking the bearings of channels or of buoys, and is a very convenient and handy instrument for this purpose. Care must be taken that its readings are not affected by the presence of metal about the boat or on the person of the observer.

In estuary-surveying it is often difficult, owing to a haze hanging about over the water, to see distant objects so as to be able to read them with the instrument. To provide against this, Captain Wharton advises the use of an heliostat. By this means, in hazy weather angles may be obtained when the place from which the flash was sent was entirely invisible. On a bright day the flash from a mirror of 3 inches × 2 inches may be seen for several miles. Captain Wharton gives a design for an exceedingly simple instrument sufficient for this purpose, consisting of a looking-glass or mirror from 2 to 6 inches in diameter, mounted on a light iron tripod 2 feet 6 inches high, revolving on retaining screws. An arm projects from the stand, having a ring of flat wood with a white cardboard disc about 1 inch in diameter. A hole $\frac{3}{4}$ inch in diameter is made

in the back of the mirror, so that the light can be directed to the object required. The arm is moved until the object as regarded in the hole in the mirror is obscured by the white cardboard disc in the centre of the ring, and the flash will be thus directed in the required line.

It is a great saving of time when natural marks, such as conspicuous trees, church spires, or other prominent objects, can be made use of as stations. Where there are rocks or cliffs, lines made with whitewash are more permanent than poles or beacons; and if tree-stems, angles of houses, or other objects are whitewashed, they become much more visible. Floating beacons are often of great service in marking the position of channels where they are not buoyed. Casks can be used for this purpose, having a beacon and flag fixed on the top, and moored with a light chain to a weight or mushroom anchor.

In selecting marks for stations or in fixing beacons, these are the more visible the greater height they are raised above the surrounding surface. On the water, owing to the rotundity of the earth, an object 5 feet above the ground becomes invisible at $2\frac{1}{2}$ miles, supposing the observer's eye to be level with the water; 10 feet high at 4 miles; 15 feet at $4\frac{1}{2}$ miles; 20 feet at $5\frac{1}{2}$ miles; 25 feet at 6 miles; and 50 feet at $8\frac{1}{2}$ miles.

The following formula gives approximately the height an object requires to be above the ground to be seen at a given distance—

$$\sqrt{H + \frac{H}{2}} = M$$

where H is the height in feet above the ground.

M, the number of miles the object is distant; for example, a tower 50 feet high would be visible at 8·66 miles.

For measuring horizontal distances the 100-feet steel chain is used, the land surveyor's chain of 66 feet never being used for marine surveys.

The contour of river channels and heights of the shore and sands, as far as practicable, are obtained by levelling in the ordinary way, the channel being shown by a section, on which the bed of the river, the low-water line, the high water of ordinary spring tides and of neap tides, and of the highest recorded tides, are shown. The height of sandbanks, marshes, etc., is given by figures on the plan.

The making of sections of a tidal river occupies considerable time, as the work is much hindered by the tides. When the rise of the tide is great, the work can only be carried on for about two or three hours before and after low water.

In taking longitudinal sections, with the water-level continually varying with the ebb or flood tide, the level of the water must be taking concurrently with the soundings. Owing to the swiftness of the current, or to the obstructions on the banks and other causes, the leveller is generally unable to keep on the river-bank or to move along with or as quickly as the boat. Under such circumstances, the observer taking the soundings, choosing the first convenient or open space which the leveller can reach, places a stake at the level of the water at which the soundings were taken, and waits until the man with the level staff appears.

Where the banks are steep and the foreshore covered with soft mud, and the man holding the level staff cannot get to the water's edge, the height of the water may be read by the level from a long sounding-pole of the form shown in Fig. 55, and marked to half-inches, held to the surface of the water by a man in the boat. When the level staff can be used, it is convenient to fix it in a strong wooden crutch so as to give greater elevation, the length of the crutch being added to the figures read on the staff.

In taking cross-sections of a river, where the width is not too great, the author has found the most effective plan to be by having two strong wooden stakes driven into the banks at both sides, and stretching from these across the river a light wire rope, drawn quite tight by means of steel blocks and tackle attached to one of the posts. Along this wire is then stretched a line marked by pieces of different-coloured rag to every five feet. The intermediate distances are taken by a tape. This line should be measured after it is wetted and after being stretched, as its length will vary considerably under different conditions. The boat, being moored to the bank by a long line, can be sheared across by an oar in the stern by one man, the other guiding it along the wire rope, and the surveyor taking the soundings at regular intervals. Where the river is too wide for this operation, the position of the soundings must be fixed by a theodolite from the bank.

Taking Soundings.—Particulars of channels for the purpose of

obtaining the navigable depth of water are found by sounding from a boat either with a sounding-pole, a steel sounding-chain, or the lead-line. The latter is the instrument always used by sailors, and, where extreme accuracy is not required, is sufficient for the purpose.

The hand sounding-line for shallow water consists of a line to which is attached a cylindrical lead weight of from 7 to 9 lbs. It is made hollow at the *heel* or bottom, which is wider than the top, so that there may be inserted a lump of tallow or *arming*, its purpose being to bring up some of the bottom it touches, so that the nature of the ground may be ascertained. The line is generally 25 fathoms in length, and is marked with strips of leather and different-coloured calico or string at the 2, 3, 5, 7, 10, 13, 15, 17, and 20 fathom marks. These are known as "the marks," and a sailor, in calling out the soundings where these marks apply, uses the expression "By the mark seven," if the mark is close to the water; if more than the 7 fathoms, he calls, "and a quarter seven," "and a half seven," or "a quarter less eight," these being respectively $7\frac{1}{4}$, $7\frac{1}{2}$, and $7\frac{3}{4}$ fathoms. For the fathoms where there are no marks, he calls, "By the deep four," etc. The use of these terms is to prevent mistakes in calling out numbers which have similar sounds, such as 7 and 11, and to emphasize the number called; the word "deep" being derived from "dip," the line having to be hauled up and dipped when ascertaining the unmarked fathoms. The marks are given in the Appendix.

An engineer should never trust to the leadsman, but himself watch each cast. An up-and-down cast is the only true one, and the depth given is always in excess of the actual depth. To obtain reliable soundings, the boat ought not to move faster than is necessary to keep steering way. To heave the lead satisfactorily requires considerable practice, especially in rough water; there is a knack and sensitiveness when the lead touches the bottom, and when exactly to give the mark, which can only be acquired by practice.

A sounding-line, before being used, should first be wetted, and then its length and marks verified; and it should again be tested at the end of the soundings. If the line is new, it should be towed overboard and stretched before being used.

For taking depths in channels where the water does not exceed 20 feet, sounding-poles are used. These require some

practice in handling, and are most convenient for use when marked in feet by alternate white and black sections, the figures being cut in and painted the reverse colour to the section. If numbered on both sides and from different ends, the pole can be turned in a circle when sounding, which will be found a convenient method if the boat is small and the pole 20 to 25 feet long. The pole should be made oblong and hollowed out on the sides, as shown in Fig. 55, as this saves a great deal of rubbing on the figures. Sounding-poles should be as light as possible, white pine being the best wood for them.

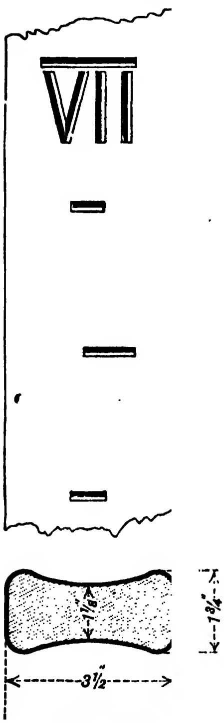


FIG. 55.—Sounding-rod.

If a strong current is running, the boat will be carried along too rapidly when sounding down a channel. To prevent this a drag may be put on the pace by trailing a weight astern.

For the purpose of marine surveys, soundings are useless unless they are corrected for the state of the tide. This is done by having observers stationed at tide-gauges, and noting every quarter of an hour the level of the water on the gauges, the observer taking the soundings also noting in his book the time at the same intervals.

In taking soundings from the coast-line across the shore and sands, a line is set out by two marks on shore, and marked on the plan. The observer sounding keeps these two marks in line, a second observer taking the bearing of the boat by a theodolite at each sounding from a convenient station, both observers numbering the figures recorded by them.

Tidal Observations.—One of the most important duties of a marine surveyor is obtaining a correct record of the rise and fall of the tides at different parts of the estuary.

In the upper part of the river this is a matter of no difficulty. Gauges are set up at various points, and all fixed accurately, by levelling to the same datum. Observers are placed at each of these gauges having reliable watches set daily to the same time. They are furnished with books in which the intervals

at which they are required to note the time are marked, and against these it is their duty to insert the height of the water on the gauge at that time.

It is very difficult to convince the men employed at the different stations of the necessity of accuracy in their observations. An assistant should visit each station at intervals daily, compare the records made, and check the watches. He should also take a copy of the observations. It is better to arrange for short intervals for the heights to be recorded, although the changes in the height during these periods may be small. If long intervals are given, the observers are apt to leave their stations and be absent at the exact time, in which case they would probably insert a figure obtained by guess-work.

These observations must be continued daily over one complete tide, that is for 12½ hours, and should extend over at least one complete set of spring and neap tides. It is, however, better to continue them over a complete lunation, as disturbing causes from wind and errors will unavoidably creep in, and the extended time gives an opportunity to check and correct these. It is very desirable to have a self-recording tide-gauge at one station, but if this is not available, the observations at the principal station should be kept up night and day. As these observations will not only be useful for the immediate purposes of the survey in hand, but will also afford a permanent record of the tidal conditions of the port, and give information of value to the harbour-master and pilots, the question of expense should not prevent the work being done thoroughly and completely. In fixing the gauges care must be taken to select places where there will be as little disturbance as possible in the water.

When tidal observations are intended for scientific purposes or determining accurately the establishment of a port, greater precautions have to be taken, and for these reference may be made to Major Baird's Manual for Tidal Observations.

In an open estuary it is often very difficult to fix a reliable gauge and obtain satisfactory observations. Soundings obtained from a boat are only approximately correct. Gauges are apt to be washed away or run over by vessels at night. The method generally adopted is to fix a long pole properly marked with black and white paint, having a broad base formed in the shape of a cross, and weighted and held in place by wire-rope stays to mushroom anchors. If this can be successfully launched and

set upright, the height of the water on the gauge can be read off by the aid of a binocular glass by an observer stationed in a boat moored sufficiently near. This can only be done in calm weather and in summer, when the days are sufficiently long to give 12 hours' light. The datum of the gauge can be fixed by carrying the datum-level to a fixed point on the shore, as near as possible to the gauge, and taking the rise of tide at high water above this mark and on the gauge at the same time. The period of neap tides is most suitable for observations of this character, as the changes in level are less and the period for observation longer than at spring tides. This level can only be found in perfectly calm weather, and should be checked on several occasions.

The observations thus obtained require for use to be graphically produced in a tidal diagram, giving the horizontal distances of each station, the vertical rise and fall, and the time. Different diagrams will be required for rising and falling tides, and for springs and neaps. The diagrams may either give the actual state of the tide on any particular day, or a mean result of two or more observations. The latter plan is the most useful record. Whichever plan is adopted, it should be so stated on the diagram. The diagram of a rising spring tide given in the illustration of the Mersey (Fig. 67) will be sufficient to indicate the manner in which a tidal diagram is constructed. The illustration in Fig. 35 shows the use of a tidal diagram for ascertaining the depth of water available for a ship going down a river. Similar diagrams can be constructed for a rising tide, and for springs, neaps, and mean tides. The diagram in Fig. 56 shows graphically the state of the tide at different parts of the river at the same time, the height of high and low water at each station, and the time which elapses in the propagation of the tidal wave.

Velocity Observations.—The velocity of a current is obtained either by means of floats or by current-meters.

There are various forms of meters in use, the principle on which those generally in use act being by the revolution of a screw actuated by the current. The shaft of the blade is connected by a wheel with a dial on which the number of revolutions is recorded. The blades are released when under water by pulling up a spring with a cord attached to it, and letting this go again when the period of observation is completed. Or the mean velocity is obtained by alternately raising and

lowering the meter from the surface to the bottom when in gear. Other meters are constructed to work by electrical agency, connection being made by wires between the meter and a dial on board the boat.

For ordinary observations in shallow water, the rod to which the meter is attached can be held by the hand; but where the

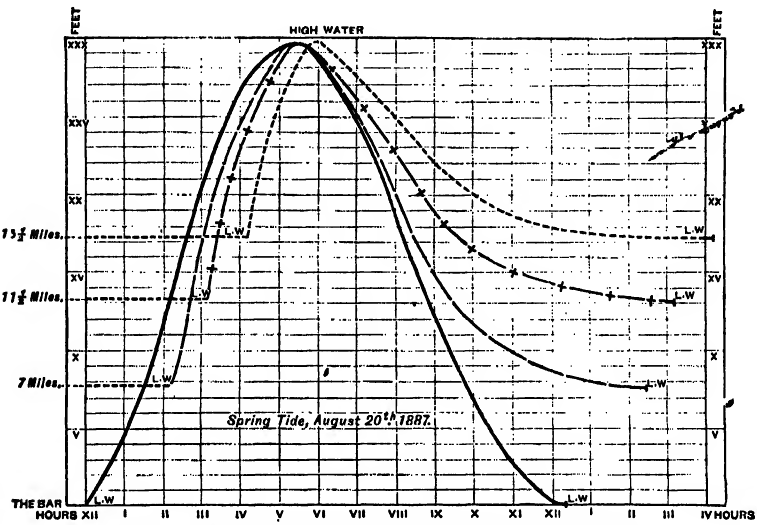


FIG. 56.—Diagram showing rise and fall of a tide at different stations.

current is strong and the depth exceeds a few feet, a line must be attached to the bottom of the rod and fastened to the boat, the length being sufficient to keep the rod vertical at the required depth. The manner in which the current-meter was worked while taking the velocity observation in the Paraguay is thus described by Mr. Revy, and is stated never to have failed from the first trial to the last observation; it worked well in depths of from 10 to 100 feet, and in currents of from 1 to 5 miles an hour. By this mode all the currents could be integrated from the surface to the bottom in a vertical plane, and the absolute mean be found. A bar of iron, about 2 inches wide by ½ inch thick and 9 feet long, with a hole drilled at each end, had a short piece of round wood attached to it in the centre which fitted into the socket of the current-meter, allowing it to revolve as on a vertical spindle. To each end of the bar cords were attached with marks one yard apart. From a platform resting on two small boats moored on the line of section, the bar

with the meter attached was lowered by two men, one at each end, the men lowering the apparatus according to the marks on the cord, each to the same depth. A third boat was moored about a hundred yards higher up on the line of the current, from which a cord reached to the bar and was fastened to the hole in its end, which prevented the current from carrying the bar and meter. By raising and lowering the bar with the two cords, the apparatus was kept in a vertical plane. The length of time the meter was allowed to remain in the water was five minutes, but observations for the purpose of checking only lasted only one minute.

As the blades of the screw are often checked or stopped by weeds or sand, it is never safe to rely on a single observation; and when a second observation differs from the first, they should be repeated until a fair mean is obtained.

The various descriptions of meters in use will be found described in the following papers in the *Proceedings of the Institution of Civil Engineers:* "Measurement of Velocity for Engineering Purposes," by Professor Hele Shaw, vol. lxix., 1881; "The Current-Meter of Professor Harlacher," by R. Blum, vol. lxvii. Also in Captain Cunningham's Article on "The Use of Floats for Hydraulic Experiments," in the Roorkee Treatise, 1881; in "Notes on Velocity Observations on the Irrawaddy," by R. Gordon (Rangoon: 1883); and Professor Unwin's article on Hydro-Mechanics in the "Encyclopædia Britannica."

To check the correctness of the instrument, it can be drawn through a channel of still water between two known distances, reversing the direction several times, so as to eliminate any errors likely to arise from wind or the motion of the water.

It is an open question whether the most reliable results of velocity observations can be obtained with current-meters or floats, different observers claiming one or the other as the more reliable instrument. The form of float best adapted for use is also an unsettled question.

In the Irrawaddy experiments, Mr. Gordon found the double float to be untrustworthy at great depths; and, on the other hand, that the current-meter was liable to give incorrect results owing to the spindle becoming choked with fine filaments of vegetable matter hardly discernible, or by sand and dirt.

For surface floats oranges were used on the Clyde by Mr. Deas. The author has found that ordinary pint bottles, filled

with water sufficiently to keep about an inch of the neck out of water, give more satisfactory results than floats which merely lie on the surface, as they are less affected by the wind. If a piece of red rag be fastened to the cork, it assists in tracing their progress. The author's practice has been to start two or more floats from the same station from the centre and sides of the river, and to take the mean of the results.

Where the bottom velocity is required, floats made in the form of a disc or cylinder and weighted to sink in the water, and attached by a thin wire or cord to another float on the surface, only of sufficient size to maintain the wire vertical, have been used. The float used in the Irrawaddy experiments is shown in the illustration (Fig. 57). The lower float was a cylinder of wood, 12 inches long by 6 inches diameter, made hollow at the bottom, this space being filled with sufficient clay to cause it to sink. The surface float was a disc of wood, 6 inches

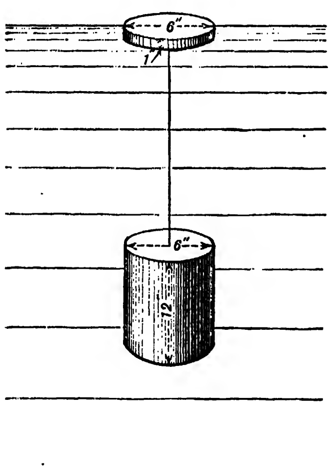


Fig. 57.

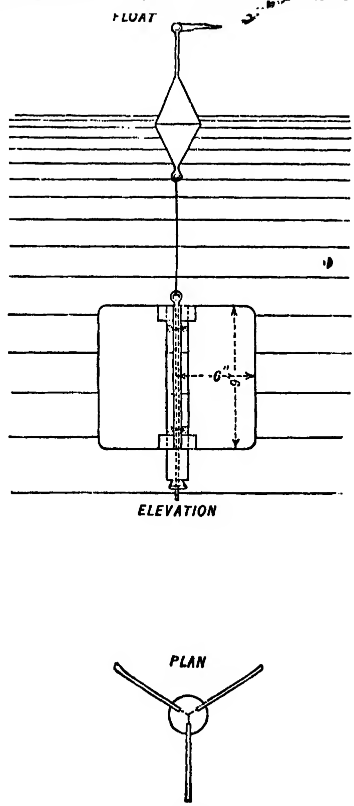


Fig. 58.

diameter and 1 inch thick. The two were connected by a cord $\frac{1}{16}$ inch thick. This float was used for depths varying from 17 to 80 feet. The author has found the form shown in Fig. 58 a more convenient and satisfactory float. The lower part

consists of three blades, 9 inches deep and 6 inches wide, of thin sheet brass; these are kept at an angle of 60° with each other by means of two collars which slip on them, and can be removed when not in use, so as to allow the blades to lie flat. The blades are connected to the top float by means of thin copper wire.

For obtaining the mean velocity of the stream, the simplest form of float is one composed of pointed rods about 1 inch in diameter and each 3 feet long, as shown in Fig. 59. The lower rod is made of brass tube, so that it can be weighted with shot to sink it to the necessary depth, the quantity varying with the depth and number of rods attached. Each rod fits into a socket, and is secured in place by a pin. The top rod has a wire which projects above the water, and carries a small red flag by which its progress can be followed. This rod, reaching from the surface to as near the bottom as the shoals in the channel will permit, is acted on by the whole vertical current, and gives therefore the mean velocity, and, being completely immersed in the water, is not affected by the wind. Being made in short lengths, it is convenient for transport on occasions when only a limited number of observations are required.

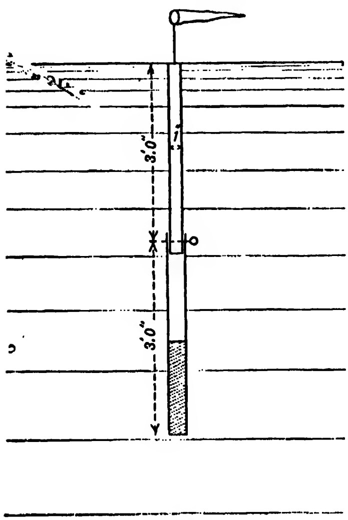


FIG. 59.

For continuous observations, where the floats are intended to remain in the channel and float up and down with the tide, these should be made of a solid log of wood about 12 inches square, and of a length equal to the shoalest depth of the channel at low water, weighted so as to float vertically and be immersed, leaving only sufficient of the float out of the water for the observer to watch its course. The visible part should be painted white, and, if the observations are continued during the night, a small lamp should be fixed on the top. The course of the float must be watched by a man in a boat, who should be instructed never to touch it unless it becomes stranded, or

damaged, or sent out of its course by the traffic or otherwise. Floats of this kind were used for the tidal observations made on the Thames and on the Clyde.

In estuaries, in order to follow the direction and velocity of currents through different channels, floats of a larger character are required. For this purpose small barrels or buoys may be used, having as much immersion as the channel will allow, and marked by small flags attached to rods on the top.

Where the float traverses a considerable distance, as in an estuary, the time of departure and arrival is all that is required. In a river-channel where the velocity has to be calculated from a short course, greater care has to be exercised, as the time must be reckoned by seconds. For this purpose it is best to take the longest stretch of straight water that can be obtained. Poles are fixed on each bank, and the distance accurately measured. In a small river the time of the float passing the poles can be noted by the eye, but in wide rivers it becomes necessary to use a theodolite at each station, the observer at the lower station denoting the time of the passing of the float by dropping his raised arm or lowering a flag.

A chronograph independent of any other movement except that for recording seconds and minutes, and which can be set in motion and stopped by merely pressing on the knob under the handle, is the most convenient instrument for taking the time. These can be obtained now at a very small cost.

Samples of Water.—It is frequently necessary, and always desirable, to obtain samples of the water for the purpose of ascertaining the amount of detritus in suspension, and its character, whether sand or alluvial matter, in order to trace the source of supply.

For this purpose the samples should be taken not only from the surface, but from as near the bottom as practicable.

For temporary purposes, or when other means are not available, this may be done by means of a glass bottle, such as used for aërated waters. Two cords are used, one attached to the bottle and the other to the cork, which is so fitted as to be easily withdrawn. The bottle being weighted and lowered to the required depth, the line attached to the cork is then pulled and the cork withdrawn, and after a short interval the bottle drawn into the boat.

The instrument used by the author, and which he has found

to answer all purposes, consists of a zinc vessel 7½ inches long by 5 inches diameter, holding about half a gallon, and weighted at the bottom. A weighted wooden cone-shaped valve 2 inches diameter works in the top cover, which is attached by screws, so as easily to be removed for emptying the vessel. To the top are attached three stout brass wires, which are joined together in a ring, to which is attached the cord for lowering and raising, a second cord being attached to a ring in the valve. When the vessel is lowered to the required depth, the cord attached to the valve is drawn up until the valve is lifted sufficiently for the water to enter; the cone prevents it being entirely withdrawn, and on the cord being released it falls back in its place. The size and shape of this instrument are the same as the lower part of Fig. 60.

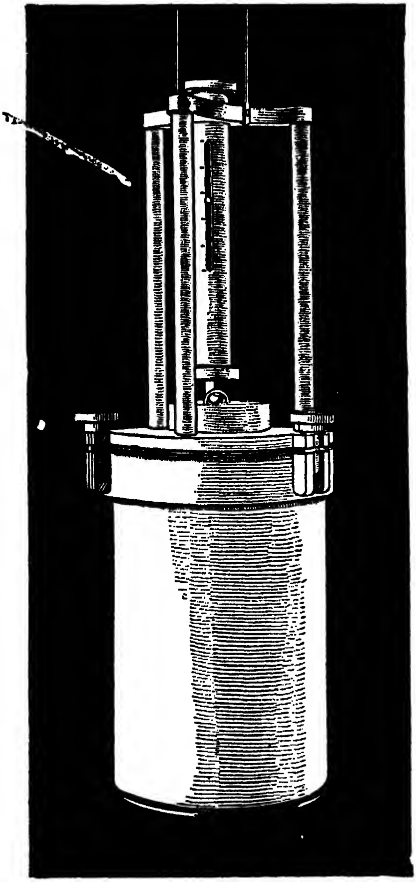


FIG. 60.—Bottle for taking samples of water.

An improvement on this instrument has been made by Mr. Herbert Wheeler, C.E., the valve being actuated by a catch attached to a spring, which acts automatically and is so regulated as to release the catch at any required depth. The principle of construction is as follows, Fig. 60 being an illustration of the instrument:—

The opening into the bottle is closed by means of a double valve, kept in place by a phosphor-bronze spring, which can be set to any required tension by means of a milled wheel at the top. When the bottle is lowered and reaches the depth to which the spring has been set, the pressure of the water acting on the surface of the valve overcomes the resistance of the

spring, and the valve moves down until it releases the catch connecting it to the spring; this allows the inner valve to open and the bottle to fill. On being removed from the water, the lid is unscrewed, the top removed, and the bottle can then be emptied. When not in use, the upper part reverses and fits into the bottle.

For obtaining an average sample in shallow water, the author has sometimes used a brass tube $1\frac{1}{2}$ inch in diameter, having a valve at the bottom opening upwards. This, being lowered to the bottom and drawn up, becomes filled with a complete section of the water. The pipes are made in short lengths connected by screw unions.

Several wide-mouthed bottles are required for holding the samples, and where a large number of samples are taken, those first placed in the larger bottles, after standing a sufficient time for the water to become clear, can have the clear water withdrawn and the samples placed in a smaller bottle, each being first carefully labelled with the locality, time, depth, state of tide, and the original quantity of water. By the use of these small bottles much less space for storage is required, and they are much more easily transported. The author has found a wooden case containing 12 bottles about $10\frac{1}{2}$ inches high by 4 inches in diameter, and holding about half a gallon, and 12 smaller bottles, about 4 inches high and 2 inches diameter, a very convenient arrangement. The case has divisions in which the bottles are fitted, and will stand a good deal of knocking about in a boat without fear of the bottles being broken.

When the sediment has all settled at the bottom of the bottle, the clean water is drawn off from the larger bottles with a syphon, and, if only small in quantity, is filtered through filtering-paper, dried, and then weighed. The filtering paper has to be first carefully weighed, placed in a funnel, and the water and sediment poured on to it. To provide against holes being broken in the paper, it is advisable always to use a layer of paper in the funnel under that on to which the water is poured. Where the quantity is great, it has to be dried in a clean shallow copper or other metal vessel. The proportion of sediment to the quantity of the water in which it was originally in suspension is reduced to the number of grains per cubic foot or gallon of water.

There are 7000 grains in 1 lb. avoirdupois; a pint of water

contains 34·66 cubic inches; a gallon 277·274 inches, or 0·16 cubic feet, and weighs 10 lbs. One cubic foot of fresh water weighs 62·425 lbs.; of sea water, 64·11 lbs.

The method adopted on the Mississippi survey was as follows: Three stations were selected, two near the banks, and one in the middle of the river. Samples of water were taken at the surface, mid-depth, and bottom. The samples were taken in kegs weighted at the bottom, and provided with a large valve opening upward fixed in both heads. When the keg reached the surface the water was thoroughly stirred, and a bottle filled from it. One hundred grammes were measured from each sample and preserved in a precipitating-bottle. After receiving six days' contributions, these bottles were set aside for two weeks to settle. The greater part of the clear water was then removed by a syphon. The remainder, after thoroughly shaking, was poured upon a double filter composed of two pieces of filter paper of equal weight. After being dried, the two papers were separated and placed in opposite sides of a pair of scales. The difference in weight gave the weight of the sediment.

To ascertain the amount of alluvium in suspension in the Seine, a thousand samples of the water were taken by M. Belleville, in 1882, at different stations along the river. The samples were taken at one metre above the bottom, and the same distance below the surface. The quantity of sediment was estimated by the height of deposit found after the water had remained twenty-four hours in a graduated glass tube. With alluvial matter it was found that the settling which continued after twenty-four hours attained about one-tenth of the original quantity, depending on the amount of clay, and vanishing to nothing as the sediment became more sandy. The sediment in the tubes was reduced by calculation to the number of cubic centimetres to a litre of water. The weight of the sediment was obtained by weighing some of the samples, and averaged as follows:—

WEIGHT OF A CUBIC CENTIMETRE OF DEPOSIT AFTER TWENTY-FOUR HOURS.

	Grammes.
Mud, very thin	0·190
„ thick	0·545
Sand and mud	0·762
Pure sand	1·442

"Régime Hydraulique de la Seine Maritime," M. Belleville

Paris Congress, 1889; "Hydrographic Surveying: a Description of the Means and Methods employed in constructing Marine Charts," by Captain Wharton, R.N. (London, J. Murray: 1882); "General Instructions for the Hydrographic Surveyors of the Admiralty" (London, sold for the Hydrographic Office of the Admiralty by J. Potter: 1888); "Manual for Tidal Observations, and their Reduction by the Method of Harmonic Analysis," by Major Baird, R.E. (1886: Taylor and Francis, London).

CHAPTER XIV.

THE USE OF WORKING TIDAL MODELS FOR THE PURPOSE OF INVESTIGATING THE ACTION OF CURRENTS AND THE MOVEMENT OF SAND IN ESTUARIES.

THE action of currents in an estuary, and their effect on the movement of the sand, and on the creation and maintenance of the low-water channels, is so complex, and is actuated by such a number of causes, and varies so repeatedly under different conditions of the tides, that it is practically impossible to obtain a complete knowledge of these by any process of observation or surveying which can be applied to the estuary itself.

By means of a tidal model, it is, however, possible to bring under immediate observation the motion of the various currents during all states of the tides, and to observe the movement of the sands beneath the clear water.

The objection may naturally be raised that results attained by such means cannot bear an analogy to the actual conditions of an estuary, owing to the absence of the effect of wind and waves, and the full momentum of the tidal wave from the open ocean; and also to the necessary exaggeration of the vertical as compared to the horizontal scale.

It must, however, be borne in mind that the main features of estuaries, and the maintenance of their channels are due to the regular and constant action of the tides, and not to the intermittent action of winds and storms, or occasional heavy land floods. These agencies may for a time disturb the *régime* of the estuary, but the natural balance of forces ultimately prevails, and the channels are restored to their normal condition. This fact is shown very clearly by the working of these tidal models.

It has been decisively shown, by models working under different conditions and by different operators, that results fairly approximate to those actually in existence can be

obtained, and that the discrepancy between the vertical and horizontal scales does not materially affect the disposition of the currents or their effect on the movement of the sand.

The manner in which the particles of sand are conveyed by the water, and the form in which they are disposed under the continual alteration in the direction of the current, as bearing on the formation of bars and the maintenance of deep pools, can be watched in these tanks, and a knowledge obtained which it is impossible to derive from observations in the deep water of an open estuary.

The method of obtaining a knowledge of tidal action in estuaries was first brought before engineers by Professor Osborne Reynolds, in a paper which he read to the Mechanical Section of the British Association in 1887. In this paper Mr. Reynolds described the results which he had obtained from a model of the upper estuary of the Mersey. The subject was considered of sufficient importance to warrant the appointment of a committee to continue the investigations, and a grant from the funds of the Association to pay the cost of the apparatus and the services of an attendant. In concert with this committee, consisting of Sir J. N. Douglas, Professor W. C. Unwin, Professor Osborne Reynolds, Messrs. W. Topley, E. Leader Williams, W. Shelford, G. F. Deacon, H. R. Hunt, W. H. Wheeler, and W. Anderson, Professor Osborne Reynolds had two tanks fixed at Owens College, Manchester, which were in operation for a period of nearly two years. One of these tanks was only half the size of the other, but in other respects was worked in the same manner. The object of having tanks of different sizes was to ascertain whether the size of the model and the variation in the horizontal and vertical scales affected the results attained.

Subsequently Mr. Vernon Harcourt experimentalized on a model of the estuary of the Seine, with training walls carried in different directions from the end of the river towards the sea, the results of which he communicated in a paper recorded in the *Proceedings of the Royal Society* in 1889. The same estuary was also placed under observation in a model prepared at the expense of the French Government, under the direction of M. Mengin, the engineer in charge of the river. The author has also had the opportunity of carrying out observations and experiments in a tank constructed on his own premises.

The larger tank used for the experiments at Owens College was 11 feet $10\frac{1}{2}$ inches long, 3 feet $9\frac{1}{2}$ inches wide, and 9 inches deep. To this tank was hinged the tide-generator, which was the same width as the tank, and 3 feet $10\frac{1}{2}$ inches long. The tank was made of pine boards fastened together with screws; it was lined with calico saturated with marine glue, put down with hot irons, and covered with a coat of paraffin. The generator was suspended from two side levers supported on cast-iron knife-edges resting in grooves. The joint between the generator and the tank was covered with indiarubber, which extended up the sides. The levers were balanced with weights. The generator was actuated by a water-moter, supplied with water from a tank, into which it was pumped up again after use. The consumption of water was about one gallon to 100 revolutions. At the highest speed, two tides a minute, the motor made 200 revolutions a minute, requiring 13,000 gallons to keep it going three days. In all it made $12\frac{1}{2}$ million revolutions. To prevent any interference with the operations of the tank the top was covered with glass, and to assist in making surveys of the changes of the sand the glass was divided into squares by black thread. The tank was covered with Calais sand and with Huna Bay shell sand, about 30 bushels being required. The smaller tank was made half the lineal dimensions of the one described.

The tidal period adopted for the model was calculated from the theory of wave motions, the scale of velocity being made to vary as the square roots of wave-heights, and the velocities in the model corresponding to those in the actual estuary as the square root of the vertical scale.

Let H = vertical scale of the tank (natural).
L = horizontal scale of the tank (natural).
P = natural tidal period.
X = tidal period for tank.

$$X = \frac{\sqrt{H} \times P}{L}$$

If P = 12 hrs. 25 min. = 44,100 sec.

$$\text{Then } X = \frac{\sqrt{H}(44{,}100)}{L}$$

Taking a 30-feet rise of tide, and a vertical scale for the model of 15 feet to the inch, or 1 to 180, giving a rise of tide of 2 inches, and a horizontal scale of $3\frac{1}{2}$ inches to a mile, or 1 to

18,200; then the tidal period for the tank would be 32·55 seconds.

$$X = \frac{\sqrt{180} \times 44{,}100}{18{,}200} = 32{\cdot}52 \text{ sec.}$$

In the model of the Mersey, the outline of the coast was modelled to a scale of 2 inches to a mile, and a vertical scale of 80 feet to an inch. The high-tide depth was made equivalent to 20 feet. The tide period was 42 seconds. The floor of the estuary was laid quite level. After running a certain number of tides the sand was again levelled, and the operation repeated, fairly similar results being obtained after each trial. The sand came to a state of equilibrium after about 6000 tides. The general results were as follows: After running about 2000 tides the sands began to assume a definite shape; the circulation at the top of the flood caused a general rise of the sand on the Cheshire side and lowering on the Lancashire, after which the two sides maintained a steady condition as regards depth. During this time banks were formed and low-tide channels which resembled in all the principal features those actually in the Mersey: the eastern bank with the deep Sloyne on the Cheshire side, the Devil's Bank and the Garston Channel, the Ellesmere Channel, and the deep water in Dungeon Bay and at Dingle Point,—all were very marked in character and closely approximate to scale. Subsequently the same experiments were repeated with similar results in a larger model, in which the coast-lines were produced on a scale of 6 inches to a mile, with a vertical scale of 33 feet to the inch. The tidal period of this model was 80 seconds. By watching the motion of the water and the currents produced, the causes of all these features could be distinctly traced in the model.

In the tanks at Owens College no actual form of estuary was modelled. The main object was to ascertain whether the operations were affected by the use of models of different dimensions. The sand was therefore levelled over the rectangular tank, and the effect of the action of the water in it noted. Experiments were also made with a V-shaped estuary; with an estuary having a river with long tidal run at its head; and with a river having a flow of fresh water.

The general results attained may be summarized as follows:—

The sand assumed an inclined plane descending down the

tank in a steadily diminishing manner. There was a constant tendency for sand to work down into the generator.

The experiments made with tidal periods varying from 33 to 65 seconds, gave the same results as regards the formation of the sand.

The first result of the tide was always to dispose the sand in a continuous slope, gradually diminishing from high water to a depth about equal to the tide below low water.

The second action, to groove this beach into banks and low-water channels, which attained certain general proportions. Ripple marks were then formed, the distance between the tops of the largest being twelve times their height, which was one-fourth the rise of the tide. This was equal to 7 or 8 feet in height, and 80 to 100 feet apart.

The rippling of the sand played an essential part in determining the rate at which the distribution of the sand was effected, while the result of this action formed a conspicuous feature in the final distribution. These ripples were almost confined to the surface of the sand below low water, and very much enhanced the effect of the water to shift the sand; they also served to show by their shape in which way any shift of the sand was taking place, having always, when the sand was moving, one steep and one flat slope. When the slopes were equal it was an indication that equilibrium had been attained.

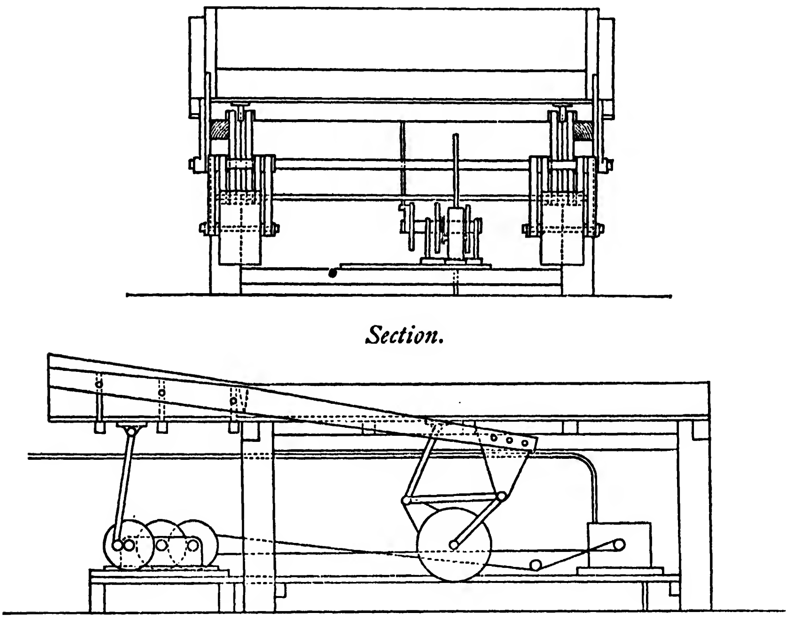
In the estuaries having a rectangular form, where the sand was spread evenly over the whole surface, after a certain number of tides there were always three or more low-water channels; whereas in the V-shaped estuary the tendency was to form one main low-water channel, generally down the centre of the estuary; but if the low-water channel went down one side of the estuary, then at the lower end there was on the other side a second channel starting at some distance down the estuary.

In the experiments where the water was allowed to run up a long tidal river, decreasing in width upwards, and discharging into a V-shaped estuary, the time occupied by the tide in getting up the river and returning caused the water to run down the estuary while the tide was low, and necessitated a certain depth of water at low water, which caused the channel to be much deeper at the head of the estuary.

The effect of admitting water into the upper part of the river showed that the stream of land water running down the sand,

though always carrying sand down, did not tend to deepen the channel in the estuary; since at every point it brought as much sand as it carried away. The principal effect of the land water was that, running in narrow channels at low water, it continually eroded the concave side, keeping the banks low, and preventing the occurrence of fixed banks and channels. The effect of land water in keeping open the upper and contracted portions of the channel was well shown by the model.

The model used by the author, shown in Fig. 61, was con-



Section.

Elevation.

FIG. 61.—Working tidal model.

structed very much on the same lines as that already described. It was 7 feet 3 inches long by 6 feet wide, and 6 inches deep. The generator was the same width as the tank, and 3 feet long. The bottom was first painted, then covered with calico while the paint was wet. The generator was balanced by two weights of cast iron weighing $1\frac{1}{2}$ cwt. each; they were connected to the arms of the generator by means of a set of differential levers, so constructed that the generator was in a state of equilibrium at all states of the tide. The machinery for actuating the generator

was driven from a small percussion motor by water obtained from the town mains under a pressure of 25 lbs. per square inch. The motor required about 60 gallons of water an hour, and ran at 350 revolutions a minute. The generating machinery was arranged to give both spring and neap tides in the proportion of 6 to 4.

The top edges of the tank were divided into inches, and a T-square was arranged to reach across the tank, also marked in inches. By this means the modelling and plotting of the various forms of estuaries could be more rapidly accomplished. The sand used was blown sand from the hills on the seashore, sifted through muslin, and well washed before being put in the tank. This kept the water clear, and enabled the motion of the sand to be seen distinctly. For modelling the coast-lines, and for training channels, small linen bags filled with sand were used.

The cost of the tank, generator, motor, and a wooden house with glass roof in which it was placed, was about £50.

The whole of the apparatus was designed by and carried out under the direction of Mr. Herbert Wheeler, C.E., the author's son, who also assisted him in making the observations and noting the results.

The general results of the observations made with this tank confirmed those of Professor Osborne Reynolds. There was always a tendency for a certain amount of sand to work downwards into the sea, as represented by the generator; the motion of the sand was confined to the first quarter of the flood and the last quarter of the ebb. When the sand attained a smooth surface there was no movement of the particles, but only when it was in furrows and ripples. The steep side of the ripples was always on the side opposite to that from which the water was coming. Under certain conditions well-developed bars were formed at the lower end of the channels; a bore always appeared in the river channels when the sections of these were small compared to the quantity of tidal water which was poured into them. In an estuary with a coast-line similar to the Wash, the tide and half-tide and currents, taking almost the identical direction of those actually prevailing, were reproduced. After running a certain number of tides an equilibrium became established, and very little further change took place, the main features remaining unchanged.

Mr. Kinipple, from experiments made with a working tidal model, has expressed the opinion that trustworthy results can be obtained from these small reproductions of estuaries, and the effect of training banks and groynes be watched with profit. The model he used differed from those already described, as being on a smaller scale and worked by clockwork. It was also provided with a glass bottom, the light being placed beneath the model in a darkened room, by which means the motion of the particles of sand could be distinctly seen.

The results obtained by piers, training walls, groynes, or from enclosures in models of this description, are not to be taken as reliable guides for carrying out works in an open estuary. They are, however, valuable aids as indicating results that may occur, and as affording suggestions which can be followed up and investigated. By altering the conditions of a model estuary by training walls in one particular part, results may ensue in other parts that had not been anticipated, but which, on carefully watching the flow of the water and the movement of the sand, can be traced to such causes as would prevail in an estuary under similar conditions. There is always an element of uncertainty as to the result of works carried out for the improvement of estuaries, and by the aid thus afforded mistakes may be avoided and waste of money prevented.

The reports referred to in this chapter are, "On Certain Laws relating to the Régime of Rivers and Estuaries, and on the Possibility of Experiments on a Small Scale," by Professor Osborne Reynolds, British Association Report, 1887; Report of the Committee appointed to investigate the Action of Waves and Currents on the Beds and Fore-shores of Estuaries by means of Working Models, British Association Report, 1889; second Report of the same Committee, 1890; "The Principle of Training Rivers through Tidal Estuaries, as illustrated by Investigations into the Methods of improving the Navigation Channels of the Estuary of the Seine," by L. F. Vernon Harcourt, *Proc. Royal Society*, 1889.

CHAPTER XV.

EXAMPLES OF RIVER IMPROVEMENT.

The Clyde affords a most remarkable instance of the results which can be obtained by the development of a small tidal river. The Clyde naturally is a very insignificant river, being only 98 miles long, and draining 945 square miles. In its original state it was fordable 12 miles below Glasgow in summer, and the channel generally was so shallow and encumbered with shoals, that barges drawing from 3 to 4 feet could only reach Glasgow on the top of a spring tide. Even after some of the worst shoals had been removed, the first steamer that navigated the river, although drawing only four feet, could not leave Glasgow until high water, and even then she frequently ran aground, and the passengers had either to wait for the next tide or wade ashore. Now the steamers plying on the river convey nearly 2¼ million passengers in a year.

The number of ships on the Register, at Glasgow, in 1810 was 24, of a total tonnage of 1956 tons, and an average tonnage of 82. The increase since then has been fairly gradual, till in 1891 the number was 1576, representing 1,316,809 tons, in addition to 309 at Greenock of 240,100 tons; the average tonnage being 815, and 19 of the vessels being above 3000 tons. The number of vessels entering the port from foreign countries and coast-wise in 1891 was—

	Vessels.	Tonnage.	Average tonnage.
Glasgow	9,075	2,711,697	300·4
Greenock	7,977	1,605,559	201·2
Total ...	17,052	4,317,256	

About a century ago Glasgow was a small city containing only about 35,000 inhabitants. The population now is the largest in Great Britain next to London, amounting with the suburbs to about three-quarters of a million.

The Clyde may be considered as the birthplace of the steamship, steam navigation having been proved as practically and commercially possible by the construction of the *Comet* in 1812, which ran on the river regularly between Glasgow and Greenock, the *Charlotte Dundas* having been run on the Forth and Clyde Canal ten years previously. From these small beginnings the Clyde has become the greatest centre of steamship building in the world, there being about 40 shipbuilding yards situate on the bank of the river, and the quantity of shipping built being greater than at any other port in Great Britain, and as great as the Tyne, the Thames, and the Mersey put together. On the Clyde have been built some of the largest passenger-steamers afloat, including the *Umbria*, the *Etruria*, the *Paris* and the *New York*, the *Lucania*, and the *Campania*.

The Clyde is also the chief seat of the construction of dredging-plant, such well-known works as those of Messrs. Fleming and Ferguson, Messrs. Symon and Co., and Messrs. Lobnitz, being situated in the neighbourhood of this river.

The tonnage of shipping constructed on the Clyde averaged 227,868 tons during the three years 1890–92.

The first attempt to improve the river was made by the inhabitants in 1566, by opening out a sandbank at Dumbuck, above Dumbarton (Fig. 62), at which they laboured for several weeks, residing during the time in temporary huts built on the river-banks. About a hundred years later the magistrates of Glasgow, who then had charge of the river, deeming it not possible to get vessels up to Glasgow, determined on making provision for them at the lower end of the river, and, after being refused assistance from the authorities of Dumbarton on the ground that the bringing of vessels there, "owing to the great influx of mariners and others, would raise the price of provisions to the inhabitants," finally purchased 13 acres of land further down on the south side of the river, where they built a harbour and the first graving dock in Scotland, and established the town of Port Glasgow. After all this had been done there remained, however, a strong desire to get vessels up to Glasgow if possible.

In 1755 Smeaton was consulted; thirteen years afterwards, J. Golborne of Chester; and three years later, James Watt. From Smeaton's reports, it appears that at the western boundary of the present harbour there was then only 1 foot 3 inches at low water, and 3 feet 8 inches at high water; and for several miles

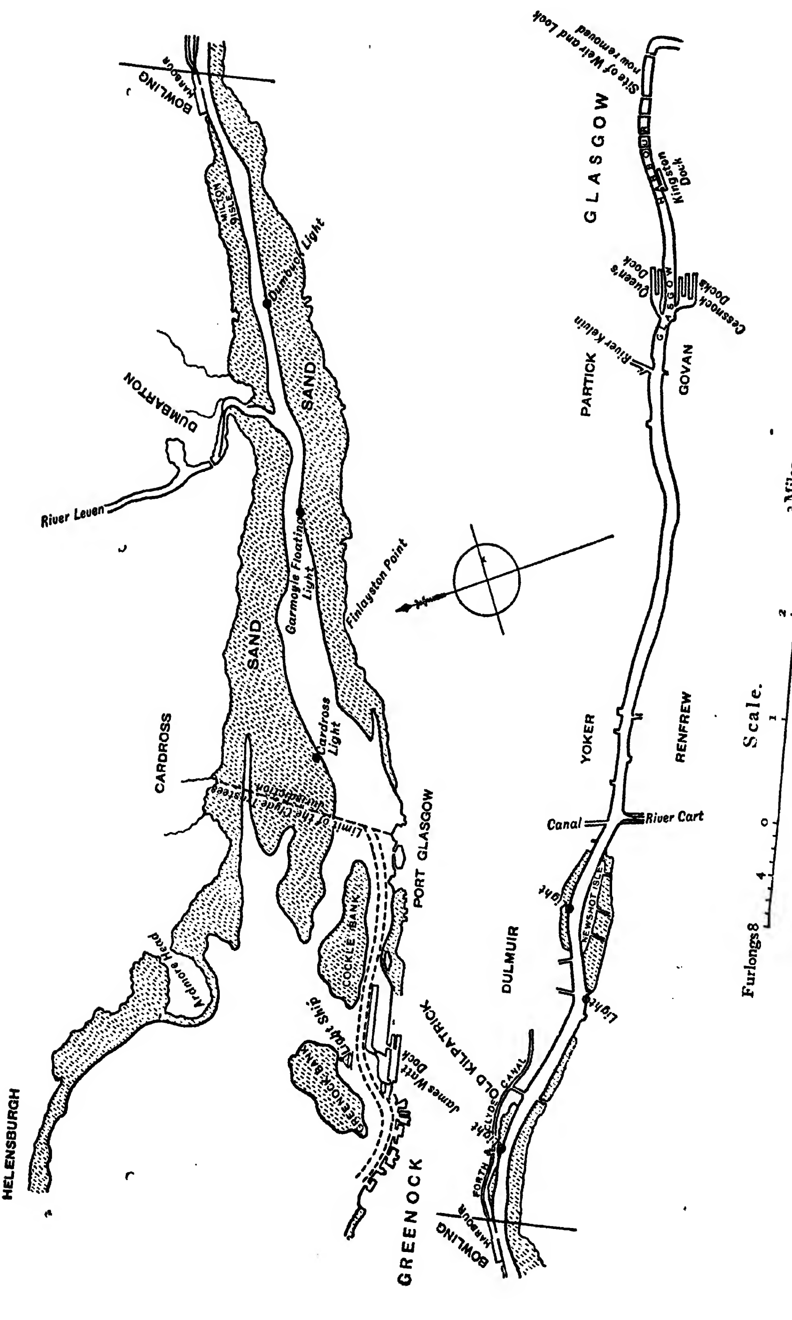


FIG. 62.—River Clyde.

down the river the depth did not exceed 18 inches at low water, and barely reached 4 feet at high water. Vessels coming with cargoes for Glasgow had to discharge into barges at Port Glasgow, as boats drawing more than 3 feet could not reach the city.

Smeaton, in his report, advised that the upper portion of the river should be canalized, and the tide excluded by means of a dam and lock at Martin Ford, 4 miles below Glasgow; the lock to be 18 feet in the clear, and to take in a vessel 70 feet long or of 100 tons, when there was water in the river to admit it. In 1759 an Act was obtained for power to construct this dam, and to cleanse, scour, straighten, enlarge, and improve the river from Dumbuck Ford to Glasgow, a distance of 12 miles.

Fortunately for Glasgow, before these works were carried out the magistrates had obtained further advice.

To Golborne may be ascribed the first real attempt at the systematic improvement of the Clyde. He convinced the magistrates that the river would be improved by contracting the channel by rubble jetties, and deepening the shoals by ploughing and breaking them up. The former Act was therefore amended by a second obtained in 1770, in which it was stated that it was intended to obtain 7 feet of water up to Glasgow at high water of neap tides. Golborne, in his report, describes the principle on which he intended to deal with the river as follows: "The river Clyde is at present in a state of nature, and for want of due attention has been allowed to expand too much, and has gained in breadth what is wanting in depth. I shall proceed on the principle of assisting Nature when she cannot do her own work, by removing the stones and hard gravel from the bottom of the river where it is shallow, and by contracting the channel where it is now too wide. By these means, easy and simple in themselves, without laying a restraint on Nature, I humbly conceive that the river Clyde may be deepened so as to have 4 feet or perhaps 5 feet up to the Broomielaw at low water."

For the purpose of deepening the river, ordinary ploughs drawn by horses were used to loosen the sandbeds which dried at low water; and for the shoals covered with water a specially made plough and harrows were used, worked by hand-capstans placed on the river-bank, the material thus loosened being carried away by the ebb current.

The wide parts of the channel were contracted by stone jetties carried out from the shore, upwards of 200, varying in length from 50 to 550 feet, being placed between Glasgow bridge and Bowling. The works carried out by Golborne, at a cost of £2300, resulted in a general deepening of the bed of the river and an increase of tidal propagation, the depth of water at Dumbuck shoal being increased, over a width of 300 feet, from 1 foot to 6 feet at low water.

The magistrates were so satisfied with the improvements made by Golborne that thirteen years later he was again called in and asked to advise as to the deepening of the channel up to Broomielaw. On making a fresh survey of the river, he found that the contraction of the channel by his jetties had resulted in further deepening, and that the shoal at Dumbuck Ford had then 14 feet, and in other parts of the channel there was as much as 20 feet. He therefore advised a continuance of the same course as had previously been carried out. The result following the carrying out of this advice was so satisfactory that the merchants and Town Council of Glasgow, in 1775, presented him with a silver cup and £1500, and at the same time presented his son, who had assisted him in the work, with £100.

Golborne was followed as engineer by John Rennie. In a survey made of the river in 1799, he found that the spaces behind the transverse jetties, which had been put in under Golborne's direction, had warped up to a very considerable extent. He advised that these jetties should be further extended so as to bring the channel to a more uniform width, and when this was done and the land at the back warped up sufficiently, their ends should be joined by low rubble training walls running parallel with the river.

The width of the channel as set out under Rennie's direction had afterwards, owing to the increase of the shipping, to be considerably increased. The land which had accreted behind the training walls was claimed by the riparian proprietors, and when it became necessary to widen the river, the Clyde trustees had to pay for the land which had thus been made by their works.

The following were the widths at low water of the river as laid out by Rennie, and as they are at the present time:—

	1807. Feet.	Present time. Feet.
In the harbour	137 ...	450
River Kelvin	180 ...	370
Renfrew Ferry	230 ...	410
River Cart	280 ...	500
Forth and Clyde Canal	440 ...	590
Erskine Ferry	504 ...	600
Dumbarton Castle	696 ...	1000

The width before the training walls were put in was 800 feet near the river Cart.

Telford was subsequently consulted, and in 1806 he reported approving the construction of the parallel training walls begun under the advice of Rennie, and advised that further works of improvement should be directed with the object of leading or bringing up a greater quantity of tidal water. He mentions in his report, as an instance of the improvement which had already resulted from the training and deepening, that a vessel of 120 tons, drawing 8 feet 6 inches of water, had been able to get up to Glasgow on an ordinary spring tide. Under his advice, a towing-path between Glasgow and Renfrew was made, having a width of 20 feet.

In 1825 the jurisdiction of the trustees was extended to Port Glasgow, and the constitution of the Trust extended. In 1858 a Consolidation Act was obtained, by which the Trust as now constituted was formed. The number of trustees consists of twenty-five, and includes the Lord Provost and nine members of the Town Council of Glasgow, the others being chosen by the various bodies interested in the shipping and commerce of the river.

In 1835 Rennie was succeeded by James Walker as engineer to the Trust. A report presented by him shows that the depth of low water in the harbour at that time was from 7 to 8 feet, and 15 feet high water of spring tides, the time of high water having been accelerated $1\frac{3}{4}$ hours by the improvements already carried out.

In 1839 the Trust obtained further powers from Parliament, to carry out improvements on the lines laid down by Mr. Walker, and these have not since been materially departed from.

Owing to the deepening of the channel from the works of improvement carried out at the end of the last century, the bed of the river became so lowered as to endanger the foundations

of Glasgow bridge. To prevent this a weir was built across the river in 1778, the crest being at the level of the original bed of the river. For the purpose of improving the harbour, this weir was subsequently removed; but, in order to hold up the water in the river for the use of the waterworks, whose supply was then taken out of it at a place about 2 miles higher up, another weir was erected in 1841, 500 yards higher up, at Stockwell bridge. Spring tides flowed over the crest of this weir from 3 to 4 feet. This weir, which in the mean time had again been moved higher up the river, was removed about thirteen years ago, and the tide allowed a free run.

Dredging was first commenced in the river in 1740, the magistrates expending the sum of £100 in procuring a flat-bottomed boat for removing the shingle from the shoals, in order to render the river more suitable for vessels coming up to the Broomielaw.

Subsequently a machine was used for loosening the material, called a "porcupine plough," which was 5 feet long, 3½ feet wide, and 1 foot 4 inches deep. This was dragged backwards and forwards over the shoals by chains leading from a barge moored in the river to the shore, and moved by men working capstans fixed on the barge. The sand and shingle were drawn to the shore by the plough, and removed by hand-labour at low water. Afterwards harrows were used, drawn by a steamboat over the shoals when freshets were running, the material being left to be carried away by the stream.

In 1824 the first steam-dredger was employed. The plant now consists of one twin-screw ladder dredger, recently added to the fleet, 200 feet long, 37 feet beam, and capable of raising 600 tons an hour in 40-feet depth of water; and four twin-screw hopper barges of 1000 tons capacity. The older plant consists of 5 ladder bucket dredgers, 18 steam hopper barges, plant for diving and lifting heavy stones, and several tugs and other craft.

The total quantity of material removed between 1844 and 1890 was 35½ million cubic yards. The quantity annually removed in recent years has been about a million cubic yards from the river, besides about half a million from the new Cessnock Dock, the total quantity to be removed from this dock and its approaches by dredging being 4¼ million cubic yards.

Of the total quantity removed from the river in recent years,

about half has been due to the matter deposited in the river from the sewers of Glasgow, and the mud washed in from the upper river. During the year 1891 it was calculated that 900,000 cubic yards was deposited matter. The remainder has been due to the deepening of the channel over the shoal places.

The material taken from the river was in the early days deposited in the shoal places at the sides. A large area of land was thus raised and made available for cultivation. Since 1862 the dredgings have been deposited in Loch Long, 27 miles from Glasgow. Objection having been made to the continuance of this by residents on the banks of the loch, the dredgings from the channel of the river will in future have to be carried to a place of deposit at a greater distance.

A great quantity of boulders, some of large size, have been removed from the bed of the river by means of the diving-bell and by cranes fixed on a barge constructed for the purpose. A ridge of whinstone which stretched across the river at Elderslie, which was 900 feet long by 300 feet wide, has been cleared away by blasting with dynamite by the aid of the diving-bell. The cost of the removal of this ridge was £70,000. The depth over the site of the ridge at low water is now 20 feet.

In the lower part of the river Clyde, below Newark Castle, which is under the jurisdiction of the Clyde Lighthouse Trustees, where the ruling depth in 1880 varied from 12 to 14 feet, a channel 492 feet wide at the bottom and 600 feet at the top has been dredged to a depth of 18 feet and 23 feet up to the James Watt Dock. The curves at Garvel and Cartsdyke Bay have been eased from a radius of 3400 feet and 1850 feet respectively to 4300 and 3700 feet. Dredging is still going on, about half a million tons being removed annually.

In 1867 the Kingston Dock, having $5\frac{3}{4}$ acres, was opened; in 1882, the Queen's or Stobcross Dock, having 34 acres; and shortly the Cessnock Dock, having 38 acres, will be opened. This does not, however, represent the accommodation given for shipping. Owing to the small rise of tide and the depth of the channel at low water, both sides of the river in the harbour afford quay-room for vessels of large tonnage, the quays extending for a length of upwards of six miles, and the water-area amounting to 160 acres. The Queen's Dock is not provided with gates, being open to the river, and the water in it rising and falling with the tides.

The first dock at Greenock was opened in 1710. The Victoria harbour was completed in 1850, at a cost of £120,000, and the Albert harbour in 1862, at a cost of £250,000. The James Watt Dock, which is 2000 feet long, 300 feet wide, with an entrance 75 feet wide and a depth at low water of 32 feet, was opened in 1885, the cost being £350,000.

The Clyde is connected with the Frith of Forth on the East Coast by means of the Forth and Clyde Canal, constructed in 1790. Its length is 35 miles. It has 20 locks 74 feet long by 20 feet wide, which admit vessels of 8½ feet draft.

The works as recommended by Mr. Walker were continued under the direction of Mr. Bold, the resident engineer, and subsequently by Mr. Brenner and Mr. Ure. In 1869 Mr. James Deas was appointed engineer to the trust. The extensive improvements which have been carried out in recent years have been executed under his direction by the staff of the Trustees without the aid of contractors.

The effect of the improvements has been to depress the level of low water at Glasgow 8 feet, and to increase the depth of water at spring tides from 3 feet in 1755 to 15 feet in 1830, 19 feet in 1850, 22 feet in 1870, and 30 feet at the present time. The depth at low water has been increased from 18 inches, and the ruling depth between Glasgow and Port Glasgow may now be taken as 20 feet at low water. It is intended to still further deepen the channel by removing the existing shoals, and so bringing the bottom to a uniform level throughout. The level of high water has been raised 10 inches at Glasgow, and the time of high water has been advanced three hours since the beginning of the present century, and three-quarters of an hour since 1835. The size of vessels which can navigate the river has been increased from 30 to over 3000 tons. The income of the Trust has risen from £68,875 in 1851 to £354,608 for the year 1891.

In one respect the Clyde reflects no credit on the Trustees or on the Sanitary Authority of Glasgow. The bright pure water that is sent down the stream from its source, and the clean tidal water that comes up through the loch from the sea, is polluted by the sewage of the vast population that resides on the banks of the river and its tributaries. Considering the enormous traffic that is continuously engaged on the river, and the immense wealth represented by the shipping and its attendant

industries, it is difficult to realize the fact that this traffic has to be conducted along a channel that is scarcely in a better condition than an open sewer, or that the Trustees should have to spend a sum estimated at from £10,000 to £12,000 a year in dredging out the solid refuse that is discharged into the river. At all times this sewage oscillates backwards and forwards with the tides; but in summer, when the quantity of fresh water coming down is small, its progress seawards is very slow, and the pollution becomes greater day by day. From experiments made with floats at different periods, it was shown that, with a moderate amount of fresh water coming down, these floats oscillated over a length of about 12 miles from Glasgow downwards, the advance being about 2·42 miles in a tide; and that sewage poured in at Glasgow did not reach Govan, 2½ miles, in less than a week, or the mouth of the Cart in less than a fortnight, and that it would take more than a month for it to get as far as Dumbarton. While the lighter matters held in suspension are thus oscillating backwards and forwards, the detritus and heavy refuse which settles on the bed of the channel has to be removed by dredging. More than twenty years ago the Commissioners appointed to inquire into the pollution of rivers, reported that nowhere had they found so great a contrast as existed between the unpolluted water which came down the Clyde, one of the most beautiful rivers in Scotland, and the "foul and stinking flood" to which it changed in the lower part of its course, and that within the space of a few miles the subject of river-pollution was exhibited in almost all its forms, and might be witnessed in every degree of intensity.

Report and Evidence of the Tidal Harbour Commissioners, 1846 and 1847. "The River Clyde," by James Deas, *Proc. Inst. C.E.*, vol. xxxvi. Pollock's "Dictionary of the Clyde" (Glasgow, 1888). Reports of J. Smeaton, 1755; J. Golborne, 1768, 1781; J. Watt, 1769; J. Rennie, 1799, 1807, 1809; T. Telford, 1806; D. Logan, 1835; J. Walker, 1836; J. Scott-Russell on "The Tidal Wave of the Clyde," 1838; W. Bald, 1839, 1844. Rivers Pollution Commission, Fourth Report (Scotland, 1872).

The Tyne.—The conditions under which the improvements in this river have been carried out differ from those of the Clyde and the Tees. In the latter rivers the gradual improvement of the tidal navigation may be said to have developed the traffic, and the industries which are now carried on along their course.

The improvement works of the Tyne followed the development of the coal trade.

The Tyne as a navigable river was, in its natural condition, in better order than either the Clyde or the Tees; the distance up the river to the principal town was only about 10 miles, as compared with 40 miles from the sea to Glasgow, and 13 to Stockton. The Tyne from very early times had been the chief port of export for coal. Until the opening out of the railway system, almost the entire supply of London and other towns remote from coal districts was conveyed from the Tyne by sailing colliers loaded from the Northumberland coal-mines. So early as 1536 a charter had been granted by Henry VIII. to the Trinity House of Newcastle-on-Tyne, with power to build two light-towers at the entrance of the river, and levy dues on the shipping for their maintenance.

Until the middle of the present century, the river seems rather to have been regarded by the Corporation of Newcastle, which formerly had charge of it, as a means of producing revenue for town purposes rather than as a national trust to be used for the advantage of the shipping interest. The improvements carried out were of a very limited character, and it was only after great pressure was brought to bear by the coal-owners and shipping interest, who showed conclusively the injury that was resulting to the whole district by trade being driven to other places where modern facilities were being afforded to the navigation, that the management of the river was transferred by Parliament to a new conservancy commission, and the works commenced which have given the Tyne a place amongst the first ports of the world. These works afford a remarkable instance of that spirit of enterprise which has in this country induced local authorities, without any aid from the Government, to carry out works of national importance. The magnificent harbour of refuge which now provides a safe haven in stormy weather for the large fleet of vessels continually navigating this dangerous part of the coast has been originated and successfully carried out by the Tyne Conservancy Commission, by funds provided entirely from local dues.

The Tyne (Fig. 63) is only a small river, 118½ miles in length, and draining 1142 square miles. It is tidal for about 19 miles. In its natural state it had a tortuous channel, generally narrow, but varying considerably in width. The entrance from the sea

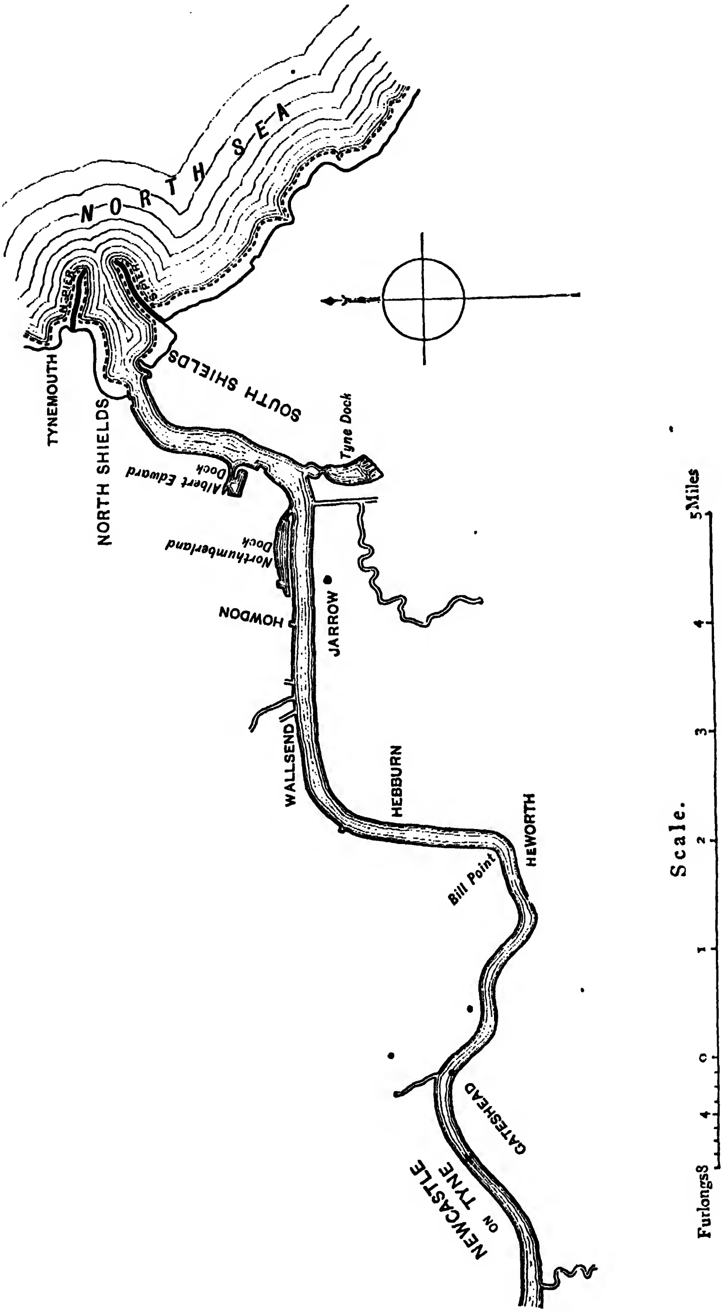


FIG. 63.—River Tyne.

was very dangerous, especially in north-east gales. The depth of water over the bar was only 6 feet at low water spring tides, and 21 feet at high water. Even after the improvements carried out by the Corporation, vessels drawing from 17 to 18 feet, after being loaded, were frequently detained for several weeks during the continuance of north-easterly gales. The largest vessels that could get to Newcastle even so late as 40 years ago did not draw more than 15 feet, and smaller river steamers drawing from 3 to 4 feet frequently grounded on the shoals at low water.

In 1832, Tyne Main Shoal had on it only 2 feet at low water of spring tides, and 13½ feet at high water. This shoal was deepened previous to 1842; but Hebburn Shoal, which then practically governed the navigation of the river, had on it only 14½ feet at high water of spring tides; Wellington Shoal, a mile lower down the river, 15 feet; and Howden Shoal, 15½ feet. In 1858 the available depth over the shoalest part of the river had been increased to 18 feet.

All this has been changed by the present Commission. The breakwaters now afford a safe harbour of refuge for vessels navigating this part of the coast, upwards of 500 vessels bound for other ports running in for shelter in the course of a year.

In Shields harbour, for a space of about 1½ mile in length, there is a pool 30 feet deep at low water of spring tides, where vessels can safely moor. There is now 20 feet at low water of spring tides over the bar, and vessels can leave the harbour at any time that it is safe for them to go to sea. The river between Shields and Newcastle, and up to the boundary of the Commissioners' jurisdiction, has been deepened by dredging and regulated by groynes and training walls, and widened in places where the channel was obstructed, by the removal of two million tons of rock. Where formerly there was only 3 feet there is now 20 feet at low water up to Newcastle, and 18 feet for 3 miles further up the river.

In 1854 the average size of the vessels trading to the port was 149 tons. In 1891 it had increased to 480 tons, and steamers of 3000 tons can be navigated along the river. Shipbuilding—which at the beginning of the present century was a considerable industry, 47 vessels, of an aggregate tonnage of 11000 tons, having been built on the Tyne in 1800—had fallen off with the displacement of wood and sails by iron and steam, so that in 1850 only seven vessels were built of a gross tonnage

of 4500 tons. Since then this industry had gone on increasing. In 1892, 73 vessels were in course of construction, of a total tonnage of 145,472 tons.

The chief trade of the Tyne is the export of coal from the Northumberland pits. So early as 1325 there is a record of coal being exported. In 1650 the export amounted to 345,550 tons. In 1800 it had increased to half a million tons. At the present time it amounts to about eleven million tons. The total tonnage of the Tyne ports is only second to London and Liverpool. The number of vessels entering in 1891 was 16,779, of a registered tonnage of 8,054,053, the average size being 480 tons.

The revenue in 1891 was £305,632. The present debt is £4,193,879, of which £750,000 is for the piers.

The early surveys or charts of the Tyne afford very little information as to its condition, or as to any record of attempted improvements. Collin's chart, made in the reign of William III., shows 21 feet over the bar at high water spring tide. Fryer's Survey, made for the Corporation in 1782, was merely a guide to the navigation, showing the available depth of water over the shoalest places. In 1813 a complete survey of the river was made by Mr. Giles for Mr. Rennie as far as Newcastle; and above this up to Ryton by Mr. Brookes in 1849.

In 1802 Mr. Chapman made a report to the Corporation on the condition of the river, and on its improvement.

In 1813 a report was made by Mr. J. Rennie, who advised the regulation of the channel by contracting the wide parts by means of transverse groynes, in the same manner as the Clyde had been treated, and the widening of the narrow places, so as to bring the river throughout to a more uniform width. The works recommended by Mr. Rennie were partially carried out by Mr. Anderson, the resident engineer of the Corporation. Considerable opposition was, however, raised to this contraction of the river, on the ground that it would result in the abstraction of one-third of the area of the river channel, and the exclusion of a large amount of tidal water, the scouring effect of which would be lost on the bar.

In 1837 Mr. Cubitt was consulted by the Corporation, and confirmed the recommendations of Mr. Rennie, but further advised the deepening of the channel by dredging.

In 1842 Mr. W. A. Brookes was appointed resident engineer.

At this period the amount allotted by the Corporation for river works was £5000 a year, out of which provision had to be made for dredging the berths at the public quays. Under Mr. Brookes' direction, the regulation of the channel as originally advised by Mr. Rennie was proceeded with. The groynes were constructed of timber, the ends being subsequently joined together when the channel had been brought to the desired width by longitudinal training walls, the materials for which were to a large extent obtained from the ballast brought by vessels coming to the Tyne to load for coals. The total amount spent on this work between 1843 and 1859 was £80,000.

The whole of the channel between Newcastle and Shields had been thus regulated by groynes and training walls in 1858, when Mr. Brookes' connection with the river terminated.

In 1844 further reports were made on the river by Mr. J. Walker and Mr. J. Murray, especially with reference to the effect of the construction of the transverse groynes which were being put in. Mr. Brookes had advised the Corporation that the effect of the contraction would result in such increased scour as would give the necessary depth for the navigation, and that ships drawing 17 feet would be able to reach Newcastle.

Mr. Brookes, in relying on the scour alone to deepen the river, proceeded on the principle "that an engineer should always seek to make the natural power of the stream do the work of deepening the channel, and should use water-power, which costs nothing, in preference to steam, for which his employers must pay." And to a very large extent the results justified this opinion, as evidence was given before the Royal Commission which sat in 1854, that 2½ million cubic yards of material had been removed from the channel by scour.

The improvements effected in the river do not appear to have kept pace with the increasing necessities of the navigation. In a report made to the Admiralty by Captain Washington in 1849, the depth on the bar was given as being then 6 feet, the same as in 1813. A comparison between the section made by Mr. F. Giles in 1813 with that made by Captain Calver in 1849 showed that, whereas a vessel drawing 15½ feet could sail up to Newcastle in 1813, the same ship could barely pass the shoals at Jarrow Slake and Hepburn in 1849.

In 1850 the Tyne Conservancy Act was passed, the management of the river taken out of the hands of the Corporation and

placed under the care of the present representative Commission. During the Parliamentary proceedings previous to the Conservancy Act being obtained, it was shown that, although the Corporation had received during the previous 40 years £957,973 in dues, only £397,719 had been expended on the river.

In 1850 power was obtained from Parliament for the construction of piers at the mouth of the Tyne. In 1813 Mr. Rennie had proposed the construction of a south pier on the Herd Sand. To this objection was raised on the ground that during north-easterly gales ships would be liable to be drifted on it by both wind and tide; and that a pier constructed in this direction would conduct the seas into the harbour. In 1845 Mr. Brookes had advised a northern pier, in addition to the southern pier on the Herd Sand, with an opening 1400 feet wide. Mr. Rendel, who had been consulted by the new Commission, advised the construction of the two piers northern and southern, but taking rather a different direction to those previously proposed, with the object of keeping the pier head as much as possible under the shelter of the Tynemouth headland.

In 1852 the Tyne Improvement Act was passed. Mr. James Walker was directed to hold an inquiry as to the designs which had been submitted by Mr. Rendel and Mr. Brookes for the piers, and also those of the Admiralty surveyors and the nautical men of the port. After this inquiry was held, Mr. Walker was finally directed to proceed with the work on lines which he had laid down, and the foundation stone of the new north pier was laid in 1854. The north pier was to extend out 700 yards, and the south pier 1400 yards, terminating in 15 feet at low water, and leaving a space of 1100 feet between the pier-heads. In 1859 the Royal Commission on Harbours reported strongly in favour of the Tyne as a harbour of refuge, and recommended that a grant of £250,000 should be made by the nation towards the cost of extending the pier to a greater distance than the Tyne commissioners contemplated. In 1859 further powers were obtained by the Tyne Conservancy for extending the north pier to a length of 2900 feet, terminating in 30 feet at low water, and the south pier to 5400 feet, still leaving the opening 1100 feet as before. This has been carried out at the cost of the Trust, no grant having been made by the Government. An attempt was at first made to let the work by contract, but it was found, after a short experience, impossible to carry out work

of such difficult and varying character satisfactorily in this way. The arrangement with Mr. Lawton was terminated, and the piers have since been carried out by the engineering staff of the Commission, under the direction of Mr. P. J. Messent.

Considerable divergence of opinion existed, not only amongst the Commissioners, but amongst the engineers consulted by them, as to the methods employed for improving the river.

Mr. Brookes had always advised that the required depth and accommodation for the navigation could be obtained by training alone, and that the greater effect of the tidal water when passing through a properly regulated channel would compensate for any loss of quantity by the areas taken from the river in the wide places. On the other hand, it was contended that the abstraction of the large volume of tidal water caused by the filling up of the wide places in the river, estimated as amounting to 1¼ millions of cubic yards, of which the river had been deprived between 1813 and 1849, must ultimately result in the shoaling of the outfall, although it was admitted it had not done so up to that time; and, further, that the process of improvement ought to be aided by dredging, which would at once give greater facilities for the navigation, and, by the increased area obtained, compensate for the tidal water prevented from entering the river by the training works.

The divergence of opinion became so strong that it paralyzed the work of the Commission, and was ultimately considered of sufficient importance, as affecting the navigation, to warrant the appointment of a Royal Commission. This Commission, after sitting at Newcastle and taking evidence, reported that they found that, notwithstanding the area of tidal water which had been excluded from the river by the training, the navigation had not been materially affected; that, after comparing the sections taken by Messrs. Rennie & Giles in 1813 with those of Mr. Rendel in 1849 and Mr. Comrie in 1854, they found a general correspondence in them; and that upon the whole very little change had taken place in the navigable capabilities of the river during the previous forty years, and that up to 1855 the river remained substantially unimproved.

In 1859 Mr. Brookes resigned, and Mr. J. F. Ure, of the Clyde, was appointed. At the time of Mr. Ure's appointment, the Tyne was perhaps in its worst condition relatively to its trade. Three vessels from America foundered on the bar within

a short time; vessels, after being loaded, remained for weeks waiting for water; and those drawing over 12 feet could not get to Newcastle except at high spring tides. Mr. Ure, bringing with him the experience of the Clyde, saw that without systematic dredging the river could never be made available for the traffic which belonged to it. In an able report he detailed what he advised to be done, and, his report being approved, he at once set to work to obtain an efficient dredging-plant for removing the shoals and deepening the bed of the river. In 1862 the piers were sufficiently advanced to allow of dredging away the sand and deepening the water over the bar.

The quantity of material annually dredged amounted for several years to from 4 to 5 million tons a year. At the present time it amounts to about $1\frac{3}{4}$ million.

In 1876 the old bridge at Newcastle, which obstructed the way, was replaced by Mr. Ure by the present swing bridge, having only four openings, the two central spans being 104 feet each.

The principal works which have been carried out for the improvement of the river are—the increase of the width of the narrows in Shields harbour from 380 feet to 590 feet; the removal of the Insand, covering 6 acres to a depth of 30 feet, which dried at low water; the removal of Dortwick Sands, which dried over 11 acres; of the Whitehill Sand, which stretched halfway across the navigable channel; of Jarrow Sand, covering 16 acres; of the Slip Sand, covering 4 acres; Longreach Shoal, a length of 2 miles; Hebburn Shoal; St. Anthony's Reach, and Brandling Reach, have all been deepened from 4 and 5 feet to 20 feet.

The harbour works consist of a north pier 3000 feet in length, and a south pier nearly one mile. The base of the piers consists of rubble stone tipped into the sea, the superstructure being formed with concrete blocks, some of which weigh upwards of 40 tons. The stone used exceeds 3 million tons in weight. The carrying out of this work has been exceptionally difficult, owing to the depth of water at the outer ends of the piers and the violence of the sea, especially in north-east gales.

The dredging has been of a very extensive character, extending not only to the deepening of the channel of the river, but also to the removal of the sand-beds which obstructed the entrance from the sea. The plant consists of six large dredgers,

ten steam-hoppers, eight steam-tugs, and forty-seven wooden barges, and cost £300,000. The material removed between 1860 and 1888 amounted to 82,684,629 tons.

Three wet docks have been constructed; the Northumberland Dock, constructed from the designs of Mr. J. Plews, opened in 1857, containing 55 acres, and having 24 feet on the sill; the Tyne Dock, the property of the North-Eastern Railway Company, constructed from the designs of Mr. F. E. Harrison, opened in 1859, having an area of 50 acres, and 25 feet on the sill; and the Coble Dene or Albert Edward Dock, constructed under the direction of Mr. Messent, opened in 1884, having an area of 24 acres, and 30 feet on the sill. The first and last were built by the Commissioners.

The effect of the improvements on the propagation of the tidal wave has been to accelerate the time of high water at Newcastle, $10\frac{1}{2}$ miles from the sea, about three-quarters of an hour, and at Newburn an hour; high water at Newcastle being now only 12 minutes later than at Shields harbour, whereas formerly it was 60 minutes later. The interval between the arrival of the first of the flood at Newcastle from Shields harbour has been accelerated nearly two hours. Formerly it was not unusual for the level of high water at Newcastle to be from 7 to 10 inches below that at Tynemouth; since the improvements it has been raised 1 foot, and low water lowered 3 feet 6 inches, making an increased range of 5 feet 4 inches. Low water has been lowered 6 feet at Blaydon, 15 miles from the sea. The volume of tidal water has been increased to over 10 million cubic yards each spring tide.

The total tidal volume sent into the river at each spring tide may be estimated at about 68 million cubic yards a day, and the ordinary fresh water discharge at 4 million cubic yards, or about one-seventeenth of the tidal water.

Since the retirement of Mr. Ure in 1870, the works have been under the charge of Mr. P. J. Messent, M.I.C.E., the present engineer to the Commission, and who had been in charge of the pier works as resident engineer from their commencement.

Tidal Harbour Commissioners' Report, 1845 and 1846; "The River Tyne," by W. A. Brookes, *Proc. Inst. C.E.*, vol. xxvi., 1867; "River Tyne Improvement," by P. J. Messent, 1888; "The River Tyne," by J. Guthrie (London, 1888). Reports of

W. Chapman, 1802; J. Rennie, 1813; W. Cubitt, 1837; W. A. Brookes, 1842; J. Walker, 1844; J. Murray, 1844; C. Washington (Admiralty Report), 1849; J. Rendel, 1851; Captain Calver, 1854 and 1872; Royal Commission, 1855.

The Tees.—Although the Tees cannot show a record equal to that of the Clyde, it affords a remarkable instance of the effect on the trade and commerce of a district due to the advantage to be gained from a tidal river when its capabilities are freely taken advantage of. The Tees is a small river, only 70 miles in length, and draining 760 square miles, and having a tidal run of 22 miles. At the beginning of the present century it was navigable for small craft of about 50 or 60 tons to Stockton, 13 miles from the sea, which was then a small town of 10,000 or 12,000 inhabitants. By means of the river a few coals were exported from the South Durham coal-fields, and goods brought for distribution amongst the farmers of Teesdale and the adjoining districts. The river was very tortuous, the entrance into the estuary from the North Sea difficult and dangerous, and the navigation amongst the shifting sandbanks between Middlesborough and the sea tedious and not unaccompanied by danger.

In 1808 the greatest depth of water at spring tides up to Stockton was 8½ feet, and vessels of 100 tons had to lighten before reaching there.

At the beginning of the present century Middlesborough had 25 inhabitants; in 1831 it was still a small village, with a population of 154, and between this place and Stockton there were only a few cottages and farm-houses scattered along the banks of the river. Middlesborough has now become an important town, having a population of 70,000.

The revenue of the Commissioners, when the works commenced in 1852, was £4,087, and the debt £102,701. In 1882 the revenue had risen to £55,780, and the debt to £611,129. Up to the end of 1890 the total expenditure on the river improvement had been £1,070,913, of which £65,012 consisted of the liabilities of the Tees Navigation Company; Parliamentary costs, £40,802; training and dredging works, £460,522; breakwaters, £289,003; the balance being for graving-docks, tugs, and other matters. The debt then stood at £838,125, a certain portion being paid off yearly. The income for the year ending 1890 was £69,697. The chief items of expenditure out of revenue

were dredging, £8,923; maintenance, £14,879; interest and redemption, £39,000.

The special industries which the Tees has developed are iron, coal, salt, and shipbuilding, about 120,000 tons of shipping being built annually.

The opening out of the Cleveland iron-mines about 1850 by John Vaughan drew the iron trade to the Tees. A continuous growth of smelting-works near the river rendered necessary better accommodation for the transport of the manufactured iron. This was still further stimulated by the discovery of the Bessemer process of making steel, which was taken up by the Tees ironmasters, making Tees-side one of the greatest steel-making districts of the country.

The effect of the works carried out has been to make the Tees a magnificent tidal waterway. The tonnage passing along the river amounted to 24,534 tons in 1804. Owing to the improvements which facilitated the navigation, it had increased to 87,823 in 1828. From this time forward, after the river was taken in hand by the Tees Navigation Company, its progress was more rapid. In 1846 the tonnage had increased to 742,521 tons. It then fell off, owing to the opening up of the railways. In 1853, the first year of the Conservancy, 3921 vessels entered the river, of a tonnage of 371,482 tons. In 1891, 4276 vessels entered the ports of Middlesborough and Stockton, of a tonnage of 1,608,449 tons, the average size of the vessels entering Middlesborough being 404½ tons, and Stockton, 255½. The average size of the vessels entering Middlesborough Dock in 1842 was 100 tons; between 1865 and 1874 it had increased to 184 tons; in 1887 the average size was 642 tons. The largest cargo loaded in a vessel between 1859 and 1864 was 705 tons; the largest cargo despatched out of the dock up to 1890 was 5000 tons of railway metal and coal.

Fifty years ago the depth up to Stockton at low water was 2 feet, and 8 feet 6 inches at high water, with 6 feet over the bar. Before the improvements carried out by the present Commission, the available depth at Stockton at low water was 3 feet, and 14½ feet at high water, whilst there was the same depth at Middlesborough at low water and 16½ feet at high water. Lower down there were two and sometimes three shallow channels, which were changed in form and depth nearly every spring tide. No less than 40 buoys were required to mark out

about 2 miles of channel. The depth over the bar was about 9 feet, shoaling on occasions to 3 feet, and the course over it varied over nine points of the compass. There is now from 18 to 20 feet over the bar at low water and 36 feet at high water, and 9 feet at low water and 25½ at high water in the river up to Middlesborough, and 18 feet at high water to Stockton. The entrance is protected by breakwaters, and is safe to enter. The channel is well lighted, and can be navigated by night as well as by day.

The first record of any attempt to improve the river was in 1769, when a Stockton tradesman, Edmund Harvey, proposed cutting through a sharp bend near Stockton, and thus "saving about two miles in three in going between Stockton and Portrack." After Harvey's death this scheme was again revived, and in 1791 Jonathan Pickernell, an engineer of Whitby, was called in to report on it. His estimate of the cost of making a cut through this bend 220 yards long was £5000. The same scheme was again revived in 1802, when W. Chapman, of Newcastle, was called in and reported favourably as to the advantage that would result from carrying it out. The tonnage in Pickernell's report was estimated at 11,000 tons. When the scheme was re-considered in 1802, the tonnage had increased so much that it was then put at 24,534 tons, and the increase from dues at £735 13*s*.

Following on Chapman's report, a bill was promoted in Parliament, and an Act obtained in 1808, under which the Tees Navigation Company was constituted as a trading concern, with power to levy dues for the purpose of improving the river and to raise £12,000.

The work of making the Maudale Cut from Blue House Point to Portrack was commenced in 1809 under Chapman's direction, and finished the following year (see Fig. 64). This cut was 220 yards long, and shortened the course of the river 2⅓ miles, and by the increased scour the channel was deepened 2 feet. The cost was £12,163. In 1824 Mr. H. H. Price, the company's engineer, proposed a second cut. Mr. R. Stevenson was called in to advise as to this proposal in 1828, and reporting favourably, further powers were obtained from Parliament in 1828, under which the Ford Causeway, or Nun's Cut, 1100 yards long, was made from Blue House Point to Newport. This shortened the distance ¾ mile, and gave from 2½ to 3 feet more water. The cost was £25,996.

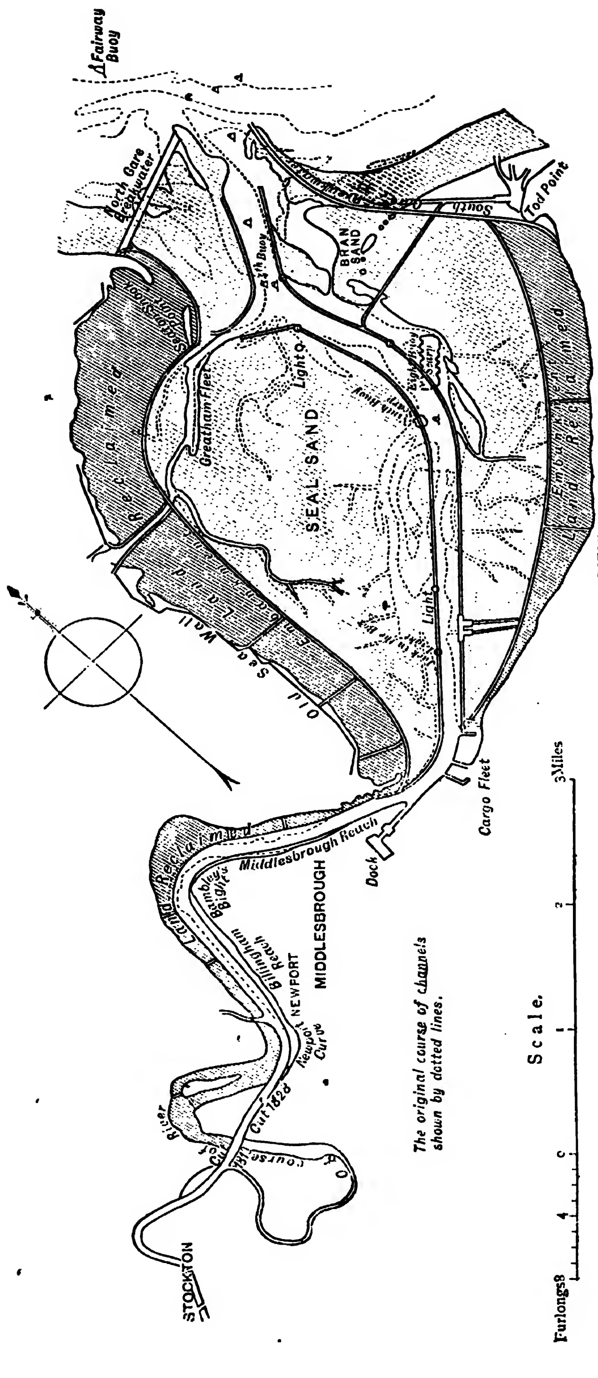


FIG. 64.—River Tees.

These improvements and the removal of some of the worst shoals enabled vessels "to reach Stockton in one or two tides, whereas before they were frequently six or eight days in making the passage from the sea to Stockton."

The improvement of the channel was continued under the direction of Mr. Price, by straightening the course and regulating the width of the river by means of transverse timber groynes, the length of which ranged from 40 to 2000 feet in length. These groynes were extended from time to time, until the channel of the river was confined to a direct course, and was brought to a uniform width. The largest of these groynes were at Bambley's Bight, where the width of the channel was very considerable, three of the groynes running out 1000 feet from the shore.

The total amount spent by the Navigation Company in improving the river was £110,000, from its establishment in 1810 till its dissolution in 1853.

In 1842 a dock of 9 acres, having a lock 132 feet long, 30 feet wide, with 19 feet of water on the sill, was constructed at Middlesborough. This dock was afterwards sold to the Stockton and Darlington Railway Company in 1852, and is now the property of the North-Eastern Railway Company, by whom it has been enlarged and the sill of the lock lowered. It now covers 15½ acres, and has 3145 feet of quays. The depth on the sill of the lock is 23 feet at spring tides, and the width 58 feet.

In 1852 an Act was obtained transferring the powers of the Tees Navigation Company to a more representative body. By a subsequent Act passed in 1875 their powers were extended. The present Trust consists of 21 members, four of whom are elected by the Stockton Corporation, four by the Middlesborough Town Council, two by the Yarm ratepayers, eight by the shipowners and payers of dues, and three by the Board of Trade. The Act provided for the raising of £207,000 for works in the river. The borrowing powers were subsequently increased to £1,000,000. The limits of jurisdiction of the Trust are from the sea to High Worsall, above Yarm, to which place the influence of the tide extends, being a length of about 26 miles.

The Tees Navigation Company had confined their attention almost entirely to works in the river above Middlesborough, and had done nothing to improve the course through the estuary to the sea, a distance of eight miles.

The navigable waterway was in such a defective condition through the estuary that it was split up into two or three channels, which were constantly shifting, and the depth was so shallow at low water that it was hardly possible for a row-boat to get along the upper part, while lower down there was only from 2 to 3 feet over the shoals.

Soon after the incorporation of the new Commission, Mr. John Fowler was appointed engineer, and under his direction the works for the improvement of the estuary were designed and carried out.

The course to be given to the permanent channel through the estuary occupied a great deal of attention. Mr. W. A. Brookes had recommended in 1846 the formation of a slightly curved channel from Cargo Fleet directly across the Seal Sand, the south training wall passing the end of the Bran Sand, and the north through the South Gare Sand. This channel would have been driven through a high bank of sand, and its axis at the lower end would have been open to the sea in a south-east direction. Mr. Johnson, the superintendent of the works, advised that the existing south channel should be improved, as being a less costly scheme, and one that could be carried out at less inconvenience to the traffic. Mr. Fowler subsequently proposed an intermediate course by a curved channel carried more to the north, and avoiding the sharp turn at the eighth buoy scarp. Mr. Johnson's plan, however, lending itself to a system of gradual improvement which commended itself to the Commissioners as being more easily adapted to the funds at their disposal, was ultimately carried out by Mr. Fowler. The work was commenced by the construction of a groyne 1400 feet long, carried across the head of the north channel, and a longitudinal training wall 1000 feet long, for the purpose of forcing the whole of the current into the south channel. This groyne was constructed of clay and stone for the first 500 feet, and the remainder of timber backed up by clay and stones. Training walls were also commenced at different parts of the channel, where it was thought they would have the most effect. These walls were subsequently joined together and extended seawards for about five miles, or within about half a mile from the pier-head at the entrance. The work of training was carried out between 1855 and 1877. The walls are from 4 feet to 7 feet above low water, and vary in height

from their base from 12 to 40 feet. About $1\frac{1}{2}$ million tons of slag were used in their construction. This slag was obtained from the ironworks in the neighbourhood, the ironmasters paying the commissioners for removing it off their premises. The slag was run hot into small iron trucks, and thence discharged into barges, and from them on to the walls in lumps weighing about 3 tons, the barges being moored to piles along the training walls. Altogether there are 20 miles of training walls above and below Middlesborough, which have been put in at a cost of £50,000.

The entrance to the estuary from the North Sea is protected by two breakwaters running out from the shore on the north and south. The Government had been strongly urged to carry out this work, on the ground that the construction of breakwaters would provide a safe harbour of refuge on the north coast. The Admiralty sent Mr. J. M. Rendel, C.E., in 1855, to report on the matter, and he advised the construction of a north and south breakwater at a cost of £300,000. The Government, however, finally declined to take the matter up, and the Tees Commissioners undertook the work. The South Gare breakwater was commenced in 1862, and finished about 1888. It runs out from the shore at Tod Point, across the Bran Sand in a north-westerly direction, curving round northwards towards the end. The length is about two miles. About two-thirds of the first part consists of slag blocks tipped direct from the trucks on to the sand, the mound being raised about 15 feet above high water. The outer part for about 3000 feet is cased with concrete, averaging 15 feet in thickness up to high-water mark, and 5 to 7 feet above this. The base of the mound above low-water level is 170 feet wide, but the toe runs out 70 to 100 feet beyond this. The top is 90 feet wide. During a heavy gale in October, 1890, about 280 feet of the wall was broken down, and the slag foundation washed away to a depth of 10 to 12 feet below low water. The damage arose from a vacant space which had been left in laying the foundation, and which could not subsequently be made solid. The breach was repaired with concrete laid in bags containing 14 cubic yards. The foot of the mound has been protected with concrete blocks, weighing from 30 to 40 tons each. Several large blocks, weighing from 200 to 500 tons, were also placed in the most exposed part. These were built in condemned ships, which were towed to the

site where the blocks were required, and then sunk, the timbers being sawn through so that the vessels might break up. The slag at first used was supplied by the ironmasters at a cost of threepence per ton; subsequently the ironmasters paid the Trust a penny a ton, and ultimately fivepence, for removing it for them. The quantity of slag used in the South Gare, $2\frac{1}{2}$ miles in length, was five million tons. The cost of this breakwater, which took 24 years to complete, was £308,653. The sum received from the ironmasters was £56,671.

The North Gare runs out from the shore at Seaton Snook, across the North Gare Sand in an easterly direction, and, when finished, is intended to be 6000 feet long, the distance between the pier-heads being 2100 feet. The mode of construction is similar to that adopted in the South Gare. The cost of construction was originally estimated at £75,000, but this has already been largely exceeded. Up to the end of 1890 about a million tons of slag had been deposited.

The deepening of the river by dredging was not commenced until 1853, when the first small dredger was set to work. This was a single-ladder bucket dredger, discharging over the end into punts. Since then the work has been carried out continuously. The quantity dredged became greater every year, being for 1854, 11,745 tons; 1864, 73,715; 1874, 848,673; 1884, 1,846,790; and the total quantity up to 1889, $24\frac{1}{2}$ millions of tons. The plant consists of 4 double-ladder dredgers, 1 Priestman grab dredger, 35 hopper barges, and 8 steam-tugs, the cost being £140,000.

A hard scarp near the eighth buoy, which interfered very much with the navigation, containing 120,000 cubic yards, has also been removed by blasting, at a cost of £27,000, leaving 14 feet at low water.

The carrying out of the groynes and fixing the channel has resulted in the deposition of a large amount of detritus and alluvial matter, which formerly used to oscillate backwards and forwards with the tides. A large area lying between the training walls and the land having become sufficiently raised by deposit of this alluvial matter to be fit for enclosure, upwards of 26,000 acres have been enclosed, requiring 10 miles of embankment, at a cost of £112,490. From the sale of this, £115,034 had been received by the Commissioners up to the end of 1890 as their share. Of the remainder, one-fourth of the

value went to the frontagers and one-fourth to the Crown. There is still an area of about 1190 acres yet to be dealt with, the value of one-half of which belongs to the Trust.

The dredging between Middlesborough and Stockton is now being actively pushed on, and is to be continued until there is 15 feet up to the dock-sill at low water at Middlesborough, 12 feet from there to Newport, and 10 feet thence to Stockton. It is also intended to remove the sharp bend at Blue House Point, and to improve the river at Ichabo Point, near Port Clarence. To effect these improvements, power has recently been obtained to raise a further sum of £150,000.

The channel of the river is lighted by means of compressed gas, for the making of which the Commissioners have a complete plant.

Report of the Tidal Harbour Commissioners, 1846. Reports of H. H. Price, May and November, 1824; R. Stevenson, 1827; W. A. Brookes, 1846. "Description of the River Tees and of the Works upon it," J. Taylor, *Min. Proc. Inst. C.E.*, vol. xxiv.; "Dredgers and Dredging on the Tees," J. Fowler, vol. lxxv.; "River Tees Improvements," J. Fowler, vol. xc.

The Mersey.—This river, although from its size not deserving attention, yet possesses characteristics of such a remarkable kind that a description of its physical conditions will afford an instructive lesson in tidal navigation. Having a drainage area hardly equal to some of the smallest tributaries of the larger rivers of the world, it yet is able, owing to the great rise of the tide, to provide a waterway to a port which stands nearly first in the world for the amount of its shipping and the size and draught of the vessels which frequent it. It is, therefore, a very striking example of the benefit conferred on a river by tidal flow.

The lower reach of the river, extending over the first 16 miles from the bar, although passing through vast beds of sand, yet maintains itself in one permanent course, and has a depth of from 30 to 50 feet at low water. The upper reach, passing through a wide sandy estuary, being acted upon by different agencies, the ebb and flood have a tendency to assume different directions, according as the tidal or fresh water has the greater influence. The consequence is that the channel is frequently shifting its position, and the waterway barely pro-

vides depth sufficient for the smallest class of vessels even at high water.

Where this river opens out into the sea, it is encumbered by one of the most remarkable examples of a bar to be found anywhere. This bar, consisting of nothing but sand, rises up above the bed of the channel for a height of 53 feet on the upper side, and 46 feet on the sea side, leaving over it a depth which has varied from 7 to 17 feet. The main channel of the river has shifted its position at various times over a space of nearly three miles, yet each new channel, as it has been formed, has also developed a new bar.

This river also stands out in contrast to the other commercial rivers in the country from the absence of any attempt on the part of the authorities interested in it to carry out works for facilitating the navigation. In addition to a very large trade with other foreign countries, Liverpool is the principal landing-place for passengers coming from or going to America. The steamship companies have lavished money without stint on the vessels engaged in the service, in order to shorten the time occupied in the voyage to the smallest possible limit; yet while hundreds of thousands of pounds have been sunk in order to save a few hours in the voyage, the vessels are frequently detained outside the approach to the river from the want of sufficient water on the bar. Until quite recently, when some experimental dredging was commenced, no works of any description had ever been attempted to facilitate the navigation by giving deep water over the bar, so that vessels might cross it at all states of the tide.

Liverpool received its first charter in 1173 from Henry II., in consequence of its importance as a port of communication with Ireland. In 1561 the merchants of the town owned only 12 ships, and the number of houses was only 138. In the middle of the fifteenth century the shipping of the Mersey is stated to have been represented by 15 vessels, of a gross burden of 268 tons. The ship-money levied in the reign of Charles I. was £25, Bristol being rated at £1000.

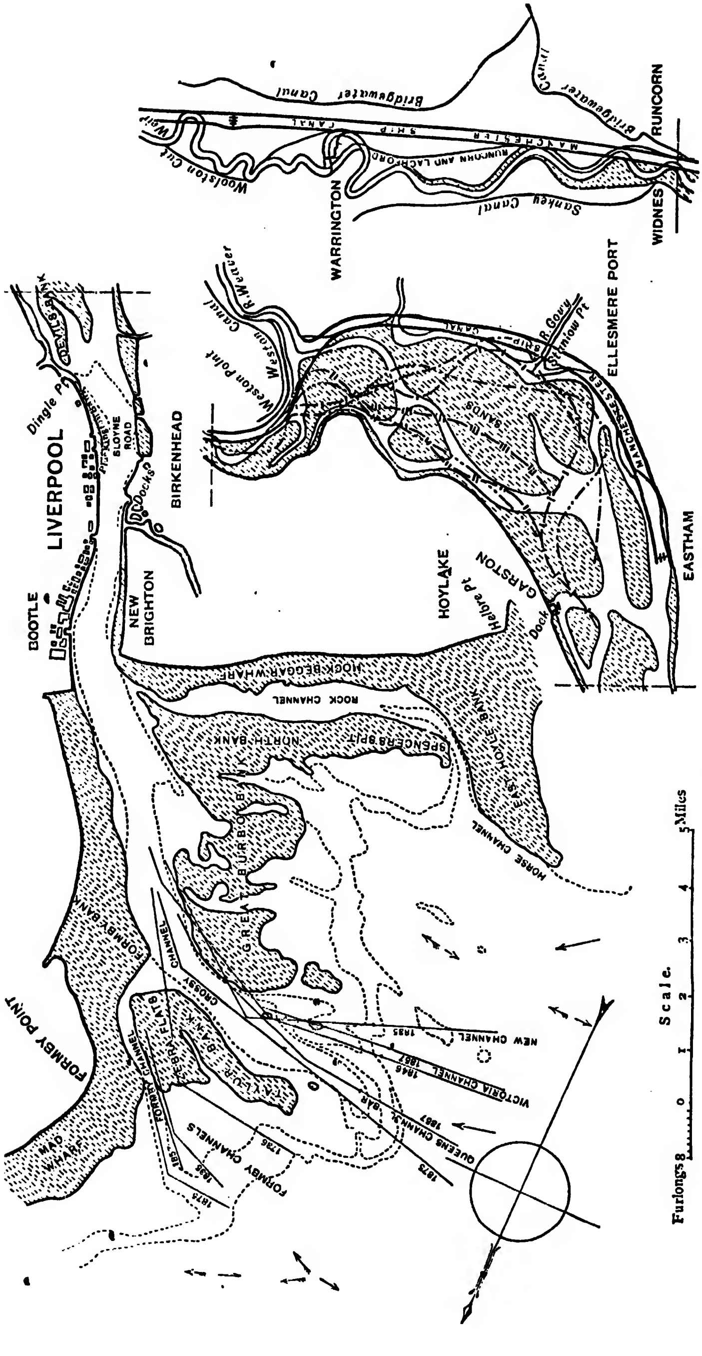
The commencement of works for the protection of shipping was made in the reign of Queen Elizabeth, when a mole was formed to protect the vessels in winter, and a quay built for loading and unloading. The first wet dock was built in 1708.

Liverpool in past times depended chiefly for its support on

vessels taking cargoes to and from Ireland, sharing this trade with Chester. While it is still the principal port for the Irish trade, its rapid growth in modern times is due to the trade with America, being the great port for the delivery of cotton, the progress being very rapid after the introduction of steam navigation. The tonnage of vessels frequenting the port of Liverpool in 1831 was 1,592,436. In 1861 it was 4,977,272, and in 1891 it was 8,623,332 tons, carried in 17,645 vessels, the average tonnage being 488 tons.

The port of Liverpool for conservancy purposes extends from the estuary of the Mersey to the extreme point reached by the tides, and includes the waters at the southern entrance to the Ribble up to Southport, and of the Dee up to Dingle. The Commissioners of the river Mersey hold their authority under the powers of an Act passed in the 5th and 6th year of Victoria. The Mersey Docks and Harbour Board have also separate rights in the river and estuary. In 1857 and 1858 Acts were passed for consolidating the docks at Liverpool and Birkenhead in one estate and under one trust. By the Consolidating Act of 1858, no less than thirty-nine Acts relating to these docks, commencing from the reign of Queen Anne, were repealed.

The Mersey derives its origin in Derbyshire by the union of two small streams, the Goy and the Thame. Passing Stockport, it is joined by the Irwell at Flixton; below Warrington it is joined by the Weaver and the Bollin. The length of the Mersey is 67 miles, and the drainage area, including the tributaries, 1285 square miles. It is tidal as far as Woolston Weir, five miles above Warrington, beyond which place the river has been canalized (see Fig. 65). Below Warrington the estuary is about 140 feet wide, increasing to 170 feet at Fidler's Ferry, and to 650 at 1½ mile lower down. It then widens out to 3500 feet, contracting to 1200 feet at Runcorn gap. Below Runcorn it widens out to 4200 feet to Weston Point; it then expands to about 1½ mile, increasing to nearly 3 miles at Ellesmere Port, and then again contracting to about a mile at Dingle Point. For the next 5 miles the channel at high water does not exceed a mile in width, and in the narrowest place is barely three-quarters of a mile. At New Brighton the channel divides in two parts, one, the Rock Channel, going to the south-west, and having a width at low water of about the third of a mile, with 2 fathoms at low-water, except at the upper end,



The position of the channel at different periods is indicated by lines as follows. 1846——, 1851—ııı—, 1861—ı—, 1866——; 1870-.-.-, 1876—ıı—.

FIG. 65.—River Mersey.

where there is a bar of rock, on which there is only about ¼ fathom.

The main channel is separated from Liverpool Bay by a range of sandbanks known as the Great Burbo, which are covered from about 16 feet to 25 feet at high water, and passes out to sea by the Queen's Channel, between the tail of these sands and others known as the Taylor Bank and Zebra Flats. There is also another narrow outlet, the Formby Channel, which has from 3 to 4 fathoms at low water, except at the upper end, where is a bar covered with only about ¼ fathom. The set of the current from Liverpool Bay is towards the main channel of the Mersey with the flood, and from it with the ebb. From the sea channels up the river entrance the current gradually increases from 2 and 3 knots in the former to 4 and 5 in the latter. At equinoctial tides it attains a rate of 7 knots in the narrowest part of the river channel. To the north of the Mersey bar the set of the current along the coast both at flood and ebb is towards and from the Ribble, and to the south the set is in the direction of the coast-line, or nearly east and west. The Burbo Sands, therefore, may be regarded as a protection from any littoral drift carried by the flood tides from being taken into the river.

The Crosby Channel, below New Brighton, has a broad navigable passage more than half a mile in width, with a depth of 26 feet at low water, increasing in places to double this. The channel from New Brighton to the outer side of the bar at the present time assumes the form of an irregular curve, having a radius of 5½ miles. Across the Queen's Channel, at its junction with the sea, is a bar formed of sand. This bar assumes a horseshoe-shape, having the convex end towards the sea in a W.N.W direction, the two inner ends being joined to the Burbo Sands and Jordan Flats. Taking the distance between these sands as one mile, the crest of the bar may be described as one mile wide by three-quarters of a mile in length, and having over it, before the dredging was commenced, at low water of spring tides, a fathom and three-quarters in the shoalest part, extending over the third of a mile, and 2½ fathoms over the remainder. On the upper side the water then deepens to 4½ fathoms for half a mile, and then to 7 and 8 fathoms. On the sea side the depth increases from 3½ to 5½ fathoms in half a mile, and then to 7 and 8 fathoms (Fig. 66).

The ridge constituting the bar always assumes the form of

an arch or loop, varying its position to the west or north-west according to the deepest depression over it; occasionally it assumes a more crescent form, as when the deepest part projects towards the west instead of towards the north-west and north. The deeper part of the ridge available for navigation is generally

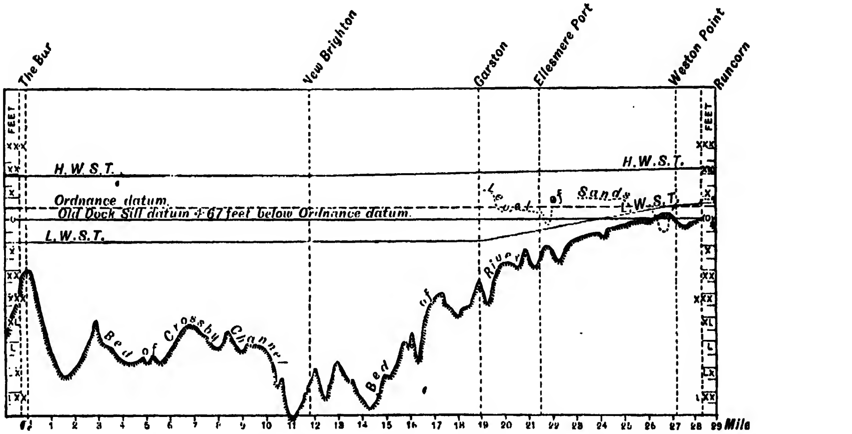


FIG. 66.—River Mersey. *Section.*

confined to a length of about half a mile, with sometimes a depth of 10 and 11 feet; but in some seasons this has been reduced to 6 feet and 9 feet, and at others has deepened to 17 feet. These minimum and maximum depths are very exceptional.

The earliest charts show that the position of the main sea channel over the bar was, two hundred years ago, very much in the same position as it is now. It appears to have varied slightly, sometimes working more to the north. About sixty years ago the channel seems to have attained its most southerly limit, being then known as "the New" or Denham's Channel. In 1842 the course was by the Victoria Channel, which went out to the south of the Little Burbo, about 1½ mile to the south of the present course. It remained in this position till 1855, when the present or Queen's Channel began to open out, the Victoria Channel being finally abandoned in 1870. The water over the bar from 1838 to 1855 varied from 14 feet and 17 feet, which prevailed for a short time in 1847, to 8 feet in 1848. The average depth over this time being 9·82 feet; the greatest average for the year being 11 feet in 1847, and the least 7·80 in

1843. After the opening of the Queen's Channel the average depth ranged from 8 to 9 feet up to 1860. It then increased to 11 and 12, the greatest annual average being in 1863, 13·30 feet. In 1866 the depth began again to diminish to 11 feet, gradually decreasing to 8·30 feet in 1869, and 7·40 in 1873 and 1874; it then increased to 9 feet up to 1883, since which it has further deepened to 11 feet. The greatest depth attained since the Victoria Channel has been opened was 16 feet during July and August in 1861, and during March, April, October, and November, in 1863; the least being 7 feet, which continued during 1873 and to the middle of 1874.

It is very difficult to assign a cause for the variation of the depth of water over the bar, but one fact may be noted—that a diminution of depth has generally occurred after heavy land floods from the upper Mersey. Thus during the great "fret" extending from 1866 to 1876, when the channel was changed from the south to the north side of the upper estuary, the water on the bar declined from 12 feet in 1866 to 10 feet in the following year, and after an exceptionally heavy rainfall in 1872 finally declined to 7 feet.

From this it would appear that when the greatest disturbance of the sands in the upper estuary took place, and the ebb water consequently carried down the greatest amount of material, this accumulated at the bar, the current not having sufficient energy to lift up the heavier particles and carry them over the ridge.

So far as any reliance can be placed on surveys made from the old charts as compared with those of the present day, it appears that, although the height and position of the sandbanks at the mouth of the Mersey may have varied from time to time, yet the total quantity of material remains the same, and the change has simply been a transport of material from one part to another.

At the time when the Victoria Channel was in existence, Captain Denham made an attempt to improve the depth over the bar by a system of harrowing, and succeeded in deepening the water over a space one mile in length; but there was so much difficulty placed in his way that he abandoned the attempt.

The question of improving the bar has naturally frequently occupied the attention of the authorities. Mr. Rennie, when consulted, expressed the opinion that the only remedy was by

concentrating the whole energy of the flood and ebb tides on the outfall by means of training walls.

The present channel over the bar having maintained a permanent position for the last twenty years, it was considered that there existed a reasonable expectation that if it were deepened by dredging, the increased depth would be maintained. The Mersey Docks and Harbour Board, acting under the advice of their engineer, Mr. G. F. Lyster, therefore sanctioned the expenditure necessary in carrying out experimental operations for this purpose. Two hopper dredgers were fitted with pumping machinery for raising the sand and carrying it away, and have since been employed on this work. The line selected for dredging was across the crest of the bar with the Formby and Crosby light-ships in line, and for a space 1000 feet in width by 3000 feet in length. It was estimated that the removal of 800,000 tons of sand would effect a deepening of 6½ feet below the shallowest place then found, giving 17 feet at low water of spring tides. The operations were commenced in the autumn of 1890. Up to July, 1893, 2½ million tons of sand had been removed, and an average depth of 20 feet at low spring tides secured. The velocity of the current through the deepened part had also been increased. Several severe gales occurred during the progress of the work without apparently affecting the increased depth. The amount expended in plant and working expenses during the first year was £15,000. The prospect of a permanent increase in depth was considered by Admiral Richards, the marine superintendent, and by Mr. Lyster, so hopeful that the Mersey Dock Board determined to spend a further sum of £65,000 in building a dredger capable of carrying 3000 tons, and in securing a depth of 30 feet at low water. A description of this machine will be found in the chapter on "Dredging."

The channel from the bar up to New Brighton has practically remained unaltered in position and depth so far as any means of comparison exist. Above this a large space on the east side, originally covered by the tides, is now occupied by the docks. This enclosure does not appear to have affected the condition of the channels except by a deepening to compensate for the decreased width. At the upper end of the narrow channel running past Liverpool, a considerable shoal known as the Pluckington Bank extends out from the east shore, causing inconvenience to the navigation and to the approaches to the

southern docks. This shoal consists of deposit covering a sub-stratum of rock. Captain Denham, the conservator of the Mersey, ascribed the formation of this shoal to the deflection of the current by the projecting rocks at Dingle Point, causing an eddy and the deposit of material on the ebb tide. This bank has a tendency to increase in size, its area having augmented in fifty years about 80 per cent., and its cubical contents 41 per cent. Many suggestions have been made for its removal. The deposit is now, to a certain extent, kept under by a series of large sluices supplied from the dock, which are opened at low water.

Opposite Pluckington Bank is the Sloyne Deep, having 8 to 9 fathoms at low water, suddenly shoaling to 2½ above Tranmere; the channel then deepens again to 4½ fathoms up to Eastham, where is the entrance to the Manchester Ship Canal. On the other side of the estuary there is also a narrow deep channel, having 4½ to 5 fathoms, known as Garston Deeps. Above this the river passes through a wide sandy estuary 30 square miles in extent, of which about 27 square miles are uncovered at low water. The highest part of the sand is not covered at neap tides. In the lowest part of the channel there is about 16 feet of water. The estuary is shut in by cliffs varying in height from 5 to 40 feet, composed of soft material, which is continually being degraded by the weather and eroded by the tides, and being removed at a rate, estimated by M. G. Hill, at one foot a year, sending into the estuary material to the extent of about 50,000 cubic yards a year. In addition to this, an enormous quantity of deposit is brought down into the estuary, due not only to natural causes, but to the sewage and refuse thrown into the rivers in the manufacturing places through which they pass. This material is carried down by the ebb during freshets, and oscillates backwards and forwards with the tides, a large quantity, 600,000 tons a year, being carried into and deposited in the docks, requiring constant dredging.

From samples of water taken from the estuary near Ellesmere Port in March, 1884, during the equinoctial spring tide, the quantity of matter in suspension varied from 20·21 grains in the gallon for the first hour of flood to about half this, averaging 12·90 to the time of high water. At high water slack the quantity was 5·25 grains, the average up to 2½ hours after high water being 6·04 grains. As the sandbanks began to uncover, the quantity increased to 15·60 grains, and from 4 hours after high water to

nearly low water, when all the sandbanks were uncovering, the quantity increased to 54·25 grains, the average being 36·94. The mean quantity on the flood was 16·01 grains, and on the ebb 22·21 grains. The river, at the time these samples were taken, was in dry-weather condition, no rain having fallen for the previous 10 days, wind light.

The channel in the upper estuary is continually shifting its position. The fresh-water floods and the tidal currents not acting along the same lines, the channel assumes a different direction after heavy floods, when the fresh water prevails over the tidal. Thus in 1829 the channel was nearly in the centre of the estuary; in 1846 it was on the north side; in 1851 it had returned to the centre; in 1861 it was working to the south, and 5 years later was close under Stanlow Point. The principal changes are shown by the dotted lines on the plan (Fig. 65). In 1866 there was a very heavy downfall of rain, followed by floods, and the channel gradually shifted from the south side of the estuary to nearly the middle in 1870. In 1872 the rainfall was exceptionally heavy; the channel continued moving, and finally reached the north side, running close under Oglet Point in 1876, thus having altered its position nearly three miles. During this great "fret" it was calculated that 5,800,000 cubic yards of sand were shifted.

The depth of water in the channel in the upper estuary in many places is not more than 3 feet. Vessels of 300 to 400 tons can reach Ellesmere Port at spring tides; above this only the smallest class of vessels can get up to Runcorn.

There is a weir across the river at Warrington, but the tidal influence extends up to Woolston Weir, 36½ miles from the bar. Neap tides do not reach further than Fidler's Ferry, 8 miles lower down. Before the construction of the Manchester Ship Canal, ordinary tides flowed up the Weaver to Sutton Weir, near Frodsham, about 2 miles above the junction with the Mersey.

The tidal water passing in and out from the sea through the narrows above New Brighton is estimated at 710 million cubic yards at spring tides, and 281 millions at a neap tide. The ordinary discharge of the upland water is calculated at from 2½ million cubic yards in 12 hours, or $\frac{1}{284}$ of the tidal flow at spring tides. The estimated quantity of tidal water flowing in and out of the bay below New Brighton is 738 million cubic yards, making a total quantity of 1521 million cubic yards.

Of this quantity, from the time of high water to $3\frac{3}{4}$ hours after, when the sandbanks at the mouth of the river begin to uncover, two-thirds of the volume of the tidal water have ebbed away at a velocity of about $\frac{1}{2}$ to a $1\frac{1}{3}$ knot. After the banks are uncovered and the ebb water is confined to the channel, the velocity increases till the maximum of 2·2 knots is reached, at $1\frac{3}{4}$ to $\frac{3}{4}$ of an hour before low water; during this period, when the maximum velocity is in operation, 162 million cubic yards of water flow out over the bar, or about $\frac{1}{10}$ of the whole quantity discharged, 71 million coming from the upper estuary, and 91 from below New Brighton. At low water the mean velocity falls to 1·9 knots. The mean sectional area of the channel from New Brighton to the bar is computed by Mr. Shelford at 144,000 square feet, the effective width of the channel at the bar being 23,200 feet, which, with a minimum depth at low water spring tides of 11 feet, would give the effective area as 275,200 feet.

The rise of spring tides at Liverpool, as given in the Admiralty tide-tables, is $27\frac{1}{2}$ feet, and of neaps $20\frac{1}{4}$ feet. Mr. Rendel, from observations made in 1844, gives the average rise of spring tides above the old dock sill as 19 feet $\frac{1}{2}$ inch, or 14·37 feet above ordnance datum; the average spring tide low water as 8 feet 10 inches below the old dock sill, or 13·51 below ordnance datum, making the rise 27 feet $10\frac{1}{2}$ inches; and the average height of neap tides as 11 feet 7 inches, or 4·91 above ordnance datum, the range of neap tides being 13 feet. The highest recorded tide given by Mr. Rendel is that of January 20, 1863, which rose 23 feet ·9 inches above the old dock sill, or 19·08 above ordnance datum, and had a range of 32 feet 7 inches. In very strong gales the tides will be affected to the extent of 5 feet. The greatest velocity of the flood through the narrows he found to be, at 3 hours' flow, $6\frac{3}{4}$ miles an hour; and of the ebb, at 2 hours after high water, 7 miles an hour.

High water spring tides, full and change, occurs at Liverpool at 11·23.

The mean of several observations made by Mr. Rendel in 1844, gave spring tides as rising 13 inches higher at Ellesmere Port than at St. George's Pier, 1 foot 10 inches higher at Runcorn, 1 foot 8 inches at Fidler's Ferry, and 2 feet 3 inches at Warrington. Neap tides rose 8 inches higher at Ellesmere Port, 11 inches at Runcorn, 10 inches at Fidler's Ferry, and 18 inches at Warrington. The mean of a number of observations

of the tides indicated that spring tides rose $10\frac{1}{2}$ inches higher in 1873 than in 1822, the level of the ebb varying only 1 inch (see diagrams of ebb and flood tides, Figs. 67 and 68). High

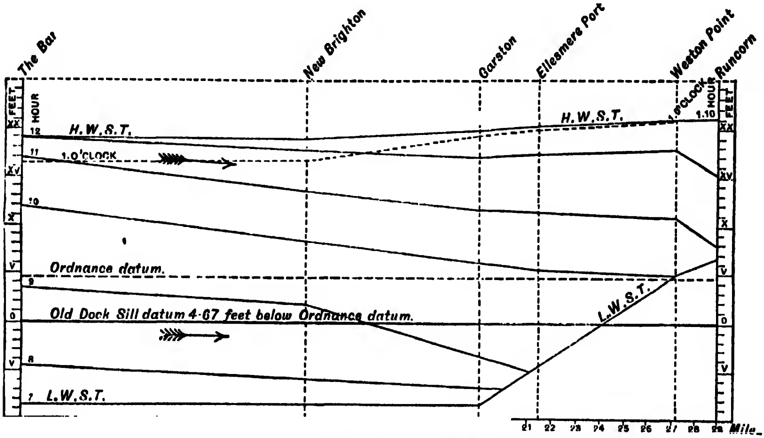


FIG. 67.—River Mersey. Tidal diagram (flood).

Note.—The lines show the relative height of the water (spring tide) in the river at corresponding intervals. The dotted line shows the level of the ebb at the bar when it is high water at Weston Point.

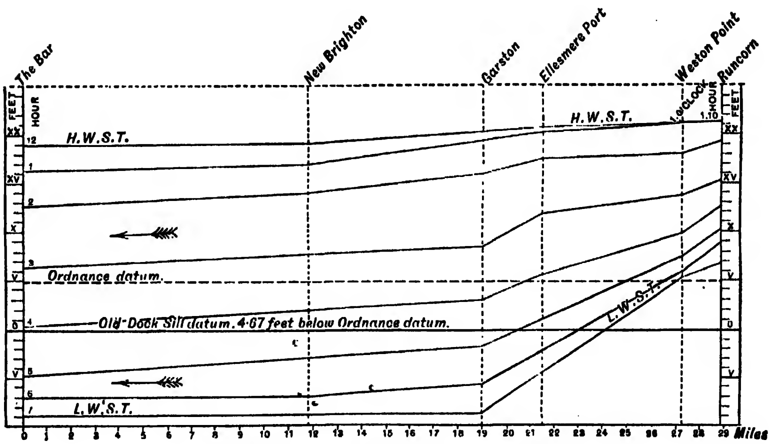


FIG. 68.—River Mersey. Tidal diagram (ebb).

Note.—The lines show the relative height of the water (spring tide) in the river at corresponding intervals.

water was half an hour later at the Rock Lighthouse than at Formby Point; an hour later at St. George's Pier and Ellesmere Port; $1\frac{1}{4}$ hour later at Runcorn and Fidler's Ferry; and $2\frac{1}{2}$ hours

later at Warrington Bridge. The tide ebbed 2 hours at the bar before high water was reached at Warrington. The first of the flood was felt 45 minutes later at St. George's Pier than at Formby Point, or at the rate of 13·33 miles an hour; 3·13 hours later at Ellesmere Port than at Formby Point, or at the rate of 3·36 miles an hour between St. George's Pier and this place; 4 hours 6 minutes later at Runcorn, or at the rate of 8·53 miles an hour from Ellesmere; 5 hours 22 minutes later at Fidler's Ferry, or at the rate of 3·60 miles an hour from Runcorn; and 6 hours 35 minutes later at Warrington Bridge, the total distance being 36½ miles, or at the rate of 2·62 miles an hour from Warrington. The total time occupied to Woolston Weir, the limit of the tide, was 6 hours 35 minutes. Spring tides flow 5 hours 20 minutes at Formby, 5¼ hours at St. George's Pier, 3 hours at Ellesmere Port, 2½ hours at Runcorn, 1·40 minutes at Fidler's Ferry, and 50 minutes at Warrington Bridge.

The inclination of the low-water line at spring tides during ordinary flow, say one hour before low water, is as follows:—

	Miles.	Fall per mile in feet.
Warrington	—	—
Fidler's Ferry	5½	1·09
Runcorn	4½	1·11
Ellesmere Port	7¼	1·65
St. George's Pier	8¼	0·36
The Bar	11	0·27
Total	36½	

Low water ebbs out lower in the upper part of the estuary at neaps than at springs. From observations made during the equinoctial tides in March, 1874, low water was found to be 5 feet lower at Warrington during a neap than the previous spring tide and 4 feet at Fidler's Ferry. At Runcorn it was 1 foot higher at neaps than springs; at Ellesmere it was 10 feet higher; at St. George's Pier, 8 feet higher; and at the bar, 7 feet 6 inches higher.

The Mersey is connected with the rest of England by a system of canals. The Leeds and Liverpool canal, which joins the river near the docks, gives access to Leeds, and, by its junction with the Aire and Calder system, with the Humber and all the centre and east of England. The Shropshire Union canal system, which permeates the potteries and extends into Wales and up to Birmingham, joins the Mersey at Ellesmere

Port, where there are docks and warehouses for the accommodation of its traffic. The river Weaver, which joins at Weston Point, is canalized, its locks being of sufficient size to admit vessels of 300 to 400 tons. A very large quantity of salt from the Cheshire mines is conveyed down the Weaver by barges to Saltport on the Manchester Ship Canal, and to the docks at Liverpool. The Bridgwater Canal, which formerly was the principal means of water-communication between Liverpool and Manchester, joins at Runcorn, where also are considerable docks; above Warrington, where the river was canalized, the Mersey and Irwell navigation goes also to Manchester.

The Manchester Ship Canal, the works for which were commenced in 1887, enters the Mersey at Eastham by means of locks capable of taking the largest class of steamers; the canal skirts the shore of the estuary to a little above Runcorn, and is semi-tidal as far as the first locks at Latchford, 20 miles from Eastham. The water in the channel is maintained at an average depth of 26 feet. At Eastham this is about the level of mean high water. There are altogether four sets of locks in addition to those at Eastham, giving a total rise from the water-level at Eastham of $60\frac{1}{2}$ feet to the surface-level of the docks at Manchester. The canal is $35\frac{1}{2}$ miles long, has a minimum depth of 26 feet, a bottom width of 120 feet. The large lock at Eastham is 600 feet long by 80 feet wide, the second lock 350 feet by 50 feet, and the barge lock 150×30. There is a clear heading under the fixed bridges of 75 feet. The traffic from the Weaver, the Bridgwater, and the Shropshire Union canals passes through the canal and joins the Mersey at Eastham.

The first intention of Mr. Leader Williams, the engineer of the canal, was to train and deepen a channel through the centre of the estuary, commencing opposite Garston, and terminating a mile above Runcorn, where the first lock was to be situated and the canal proper to commence. A single branch training wall was to commence at the head of the Sloyne deep, skirting the shore up to Ellesmere Port, whence the training was to be continued by two walls to join the main channel; a single branch wall was also to connect the main channel with the Weaver at Frodsham. From Weston Point there was only to be a single training wall on the north side to the bend in the river a mile above Runcorn, where the tidal locks were to be placed on

Astmoor Marsh. The channel through the estuary was to be 1000 feet wide at the lower end, diminishing to 400 feet at Weston Point, seven miles up, and 300 feet at Runcorn. The top of the training walls was to be 3 feet below the level of neap tides, and the channel was to be dredged out so as to give 12 feet at low water of spring tides, and 40 feet at high water. The bed of the estuary was found, by the borings taken, to consist of sand for a depth of about 14 feet, and underlying this gravel and clay, and in places soft sandstone rock, upon which the training walls would have rested.

This scheme was strongly opposed by the Liverpool Dock Board and others, the principal ground of opposition being that the proposed works in the estuary would have a damaging effect on the channel leading to Liverpool Docks and on the bar. It was contended by the opponents that the continual fretting, and changes in position which took place in the channel between Runcorn and Garston prevented accretion and maintained the tidal reservoir at its fullest capacity, and was thus beneficial to the channel below Liverpool; that, if the channel was fixed in one place, the sands would accrete, and the quantity of tidal water passing into the upper estuary be lessened in quantity, and its scouring effect on the bar be weakened. On the other hand, it was contended by the promoters that the fixing of the channel would not create any new material; that if, owing to the channel becoming fixed, a portion of the estuary became higher and were even grassed over, this would only be the result of a transposition of material, and if it was higher in one place it would become lower in another; that the dredging of the deep, wide channel necessary for the passage of large steamers would admit additional tidal water; that due to this improved channel the low water would be lowered and high water raised, admitting $8\frac{1}{2}$ million cubic yards of extra tidal water, in addition to $1\frac{1}{2}$ million cubic yards which would be admitted into the canal up to Latchford; that the tidal water would be free from the deposit now sent into the channels by the continual fretting of the sands, and would therefore be in the most effective form for carrying out of the estuary the detritus brought down the upper rivers in floods, and also that due to the erosion of the cliffs; that the result would be that, instead of a shallow channel trailing over a maze of sands, there would be a deep, regulated, energetic current, acting

always along the same line both at flood and ebb; and that the volume of water flowing up and down this deep-water channel, combined with the greater range of the tide, would be more likely to have a beneficial scouring effect on the lower channel and on the bar than the present wandering channel with its tidal water loaded with deposit from the fretting of the sands; that under present conditions, when fretting is going on, the ebb transports a large quantity of matter, either in suspension or by rolling along the bottom, which is carried to the bar, where the strength of the current is unable to lift it up over the ridge, and that it consequently accumulates, decreasing the depth of water; that, as a matter of fact, the depth of water over the bar has always been less after heavy land floods.

The influence brought to bear by the Liverpool Dock Board and the fear of any risk of damaging the access to Liverpool were sufficient to prevent the promoters obtaining Parliamentary sanction to this scheme, and they therefore brought forward the present plan, which practically leaves the tidal conditions of the estuary untouched.

The docks at Liverpool extend over a frontage along the Mersey of 6 miles, and for a width varying from 700 to 2200 feet, and cover about 381 acres. There are also docks at Birkenhead on the Cheshire side of the river, and at Garston, the latter belonging to the London and North Western Railway Company.

The first dock was constructed at Liverpool in 1708. The "Old Dock" was 4 acres in extent, and was designed by Mr. Thomas Steer to accommodate 100 vessels, affording a depth of 10 feet at neap tides. This dock has been filled up, but its sill still forms the datum for all tidal records in the Mersey, and is 4·67 below ordnance datum. The total area of water-space of the Liverpool and Birkenhead Docks is 546 acres, and the length of quays 35 miles. The lock of the Canada Dock is the largest at Liverpool, and is 498 feet long, 100 feet wide, and has 27 feet on the sill at spring tides. The Hornby and Alexandra and Langton Docks are less in size, but have about 4 feet more water on the sill. The largest entrances at Birkenhead Docks are the same size as those at Liverpool. Considerable enlargements of some of the principal locks are being made at the present time.

The number of vessels paying dues to the Mersey Docks and

Harbour Board in 1891 was 22,775, having a total tonnage of 9,772,506 tons. The receipts of the trust were £1,110,057. The outstanding loans amount to over 17 millions of money.

"The Deposits in the Mersey," by Captrin Denham, British Association, 1837; "Report on the Mersey and Irwell Navigation," by H. R. Palmer, 1840; "The Banks of the Mersey," by Boult, British Association, 1856; "The Mersey and its Estuary," by J. M. Shoolbred, *Proc. Inst. C.E.*, 1876, vol. xlvi.; "The Bar of the Mersey," by W. Shelford, British Association, Manchester, 1887; Evidence Manchester Ship Canal Bill, 1883–1885; "Recent Dock Extension at Liverpool," by G. F. Lyster, *Proc. Inst. C.E.*, 1890, vol. c.

The Dee.—Neither the size of this river, the extent of the works which have been carried out, nor the trade which has resulted therefrom, would warrant an account of what has been done; but the Dee has been so frequently quoted as an instance of the damage that has resulted to a tidal channel by combining reclamation with river improvement, and thus decreasing the tidal area, that it may prove instructive to trace out the natural features of this river, the treatment it has received, and its present condition.

The Dee is 85 miles long, and drains 862 square miles. The tidal flow is arrested at Chester by a weir, the crest of which is eleven feet above the bed of the river, over which the tidal water can partially flow at spring tides, making the tidal influence felt about seven miles above Chester; but, so far as the tidal run has any effect on the estuary, it may be considered as ending at Chester, 25 miles from the bar in Liverpool Bay.

At Connagh's Quay the duration of the flood is 2 hours 5 minutes, and of the ebb 10 hours 23 minutes; the average rise of springs is 14 feet, and of neaps 6½ feet. At Chester it is high water 53 minutes later than at Liverpool. A high spring tide rises 12 feet, and an ordinary spring tide 10 feet. The duration of the flood is 2 hours, and of the ebb 10 hours.

The flood tide sets up the river with a bore, which commences about a mile below Connagh's Quay, and attains its greatest height of two feet at Sandy Croft. It moves at the rate of 8 miles an hour.

In its natural condition from Chester down to Flint (see Fig. 69) the channel ran through an open tidal estuary, 9 miles long and about 2 miles wide, over which it was continually

changing its course, at one time running close to the east or Lancashire shore and at other times changing to the other side of the estuary. Below Flint the channel runs for 10 miles through an open sandy estuary to Liverpool Bay. For about 4 miles of its course it is divided into two low-water channels.

The width of the estuary at the lower end from Helbre

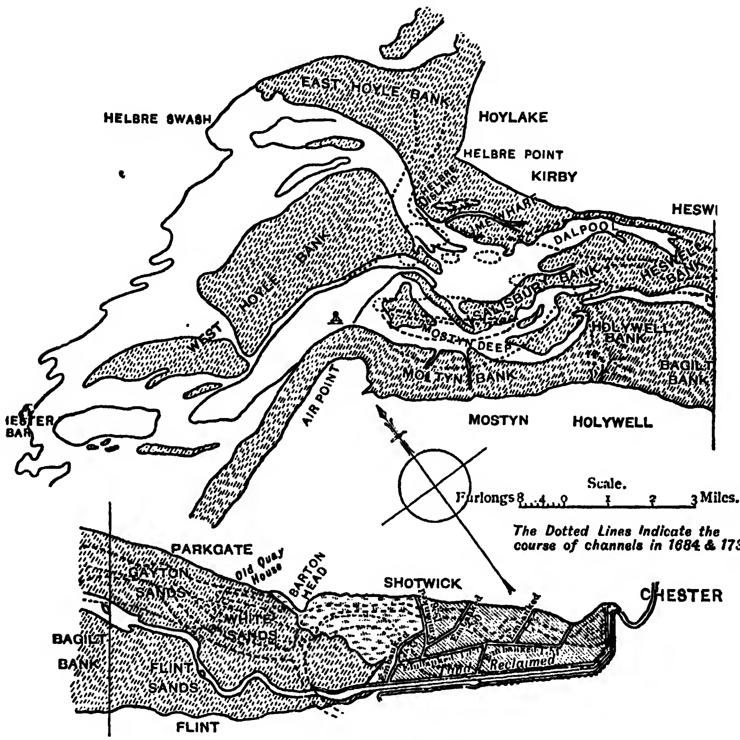


FIG. 69.—River Dee.

Island to the coast above the Point of Air is about 4¾ miles at high water. The width of the estuary decreases very regularly to 1¾ mile at Barton Head, ten miles up, or at the rate of 1584 feet per mile. The low-water channel is not well defined owing to the water being divided into two courses, but taking it to the point where the two channels unite, 4 miles above the Point of Air, the rate of decrease is about 1150 feet per mile; for the 6 miles above this the decrease is at the rate of 140 feet per mile.

The rise of tide is very great at the bar, being 25 feet at

springs, and 32 feet at equinoctial springs, and 19 feet at neaps. The rate of the flood stream in Mostyn Deep is about 3 knots.

In the reign of Queen Elizabeth a harbour was made at Parkgate, on the east side of the estuary, about 12 miles below Chester, the channel at that time passing this part of the coast. This port was the limit for seagoing vessels, and became one of the principal places of delivery for boats trading between this country and Ireland. It is, no doubt, owing to the existence of this harbour and the trade done there that a great deal of error has arisen in comparing the former trade of the Dee with that which existed after the river works were carried out, a comparison being drawn between the vessels which formerly traded to Parkgate with those which subsequently went up to Chester; and also to the fact that, owing to the permanent diversion of the river to the west side of the estuary, the harbour at Parkgate became silted up, and Flint on the opposite side of the river took its place.

The condition of the navigation of this river in 1674 is described by Andrew Yarranton in his "England's Improvement by Sea and Land," as being choked with sands so that a vessel of 20 tons could not get up to Chester, and that ships were forced to lie at Neston (near Parkgate, 11 miles below Chester), in a very bad harbour, whereby they received much damage; and navigation was so uncertain and changeable that trade at Chester was much decayed and gone to Liverpool. Twenty-six years after this the Corporation of Chester obtained an Act of Parliament, giving them powers to improve the river, the preamble of the Act stating that the navigation was almost lost and destroyed. The intention of the promoters of the scheme was to make the channel navigable for ships of 100 tons, which would require a depth of 10 feet at high water of spring tides. This Act was allowed to lapse, and nothing was done to improve the river. Ten years later Nathaniel Kinderley surveyed the river, and submitted a scheme for its improvement, which relied to a great extent on the land to be reclaimed from the estuary for the repayment of the outlay to be incurred. The Corporation did not see their way to take up the scheme, and the Dee Reclamation Company was formed in 1732, and obtained Parliamentary powers to deal with the river and embank and appropriate such portions of the reclaimed land as

at that time were not grass marsh, on condition that the new channel should have a depth of 16 feet at high water up to Chester. The company arranged with Kinderley to raise the money and carry out the work. Kinderley made a new cut for the river through the grass marshes from Chester to a little above Connagh's Quay, diverting its course to the west or Cheshire side. The length of the new cut was 5½ miles. The channel was confined to its course on the west side by a longitudinal wall 3¼ miles long, commencing 2½ miles below Chester. On the east side a continuous bank was made from Chester downwards. The river was turned into the new channel in 1737. As the land became fit for reclamation the banks were raised so as to exclude the tide, and the whole of the land on both sides down to Connagh's Quay was reclaimed and made available for cultivation.

A great deal of opposition was raised to the scheme, on the ground that the exclusion of the tidal water by the reclamation would injuriously affect the navigation through the lower part of the estuary, the quantity thus excluded being estimated by Mackay, who was employed by the opponents to make a survey of the estuary, at "no less than two hundred millions of tons of tide which will be prevented from flowing twice in 24 hours."

A space varying in width from 660 feet at the upper end to about 1500 at the lower, was left between the banks. This space was subsequently contracted by fifty groynes, placed on the west side at right angles to the channel, and averaging from 9 to 10 chains apart.

The channel is now, at low water, 220 feet wide at Chester, increasing to 290 feet a little below Queen's Ferry, about 6 miles down; it then widens out to over 450 feet for the next 3 miles to the end of the training walls, after which the low-water channel contracts to about half this width along The Causeway.

In determining the width to be given to the channel, Kinderley was no doubt more influenced by the room required for a sailing vessel to turn up the channel than by the actual requirements of the tidal flow or of the fresh-water ebb.

The sum of £80,000 was spent on the river diversion in training and reclamation works, and 4000 acres of land were reclaimed by the company, and 3000 acres by the frontagers.

The rental value of the 4000 acres enclosed by the company was put at £6500 a year in 1850.

The company received no return on the outlay of capital until 50 years after the works, were completed. When the Dee Company began their works, the various shifting channels from Flint to Chester were in such a condition as to be only navigable by small craft, vessels of any size lying at Parkgate and discharging there. From Grenville Collins' chart of 1684 and Mackay's of 1732, it appears that previous to the works carried out by the company there was 8 feet at low water and 20 feet at high water of spring tides in the navigable channel at Parkgate nearly opposite Flint, the channel then being on the Lancashire side of the estuary; 7 feet at low water and 19 feet at high water at Barton Head, 2½ miles further up; 2 feet and 10 feet at Saltney; 2 feet at low water and 9 feet at high water at Chester. After the works carried out by Kinderley, the depth up to Chester was increased to 14 feet at high water. Although this was 2 feet less than had been promised, and 1 foot less than was required to enable the company to take tolls from the navigation, it was a very decided improvement on the condition of the river before the company's works were completed.

Telford, reporting on the river in 1817, found it so improved that he remarks that the Clyde at that time had not been rendered as perfect as the Dee. In order to obtain a greater depth than then existed, he advised that a training wall should be put in at the lower end of the new works, from Connagh's Quay to Flint, in order to make the course more direct and prevent the channel from going over to the east side at Parkgate. This training wall, known as "The Causeway," was commenced and extended for about a mile and a quarter, but it has not since been carried further. In a report made by Rennie in 1837, he says that the result of the works has been to increase the depth of water between Flint and Chester, giving an available depth of from 14 feet to 14 feet 6 inches. This would show a gain of five feet on the depth in the channel before the works were commenced. Below Flint he did not find that any improvement had taken place.

In 1837 the depth of water at low water at Chester was 6 feet, and spring tides rose 13 feet 8 inches; at Flint high spring tides rose 23 feet 11 inches, and at the Point of Air 29 feet

6 inches; neap tides rising 2 feet 9 inches at Chester, 10 feet 11 inches at Flint, and 11 feet 4 inches at the Point of Air.

The depth of water in the channel has varied from time to time, being influenced to a certain extent by the amount of water coming down in floods. Owing to the shifting character of the channel below Flint, and the want of tidal backwater due to the obstruction caused by the weir at Chester, the material arising from the shifting sands brought up by the flood tide accumulates in the channel in dry weather, and remains until a heavy freshet scours it out again. In 1850, at the Admiralty inquiry held respecting the river, it was reported that at that time there was at one place a shoal in the river which reduced the statutable depth of 15 feet by 3 feet, and in other places the depth was deficient about 1 foot.

On the Admiralty chart of 1886, the depth in the channel at low water is 9 feet at Connagh's Quay, and 16 feet at Flint. The depth between Flint and Chester remains about the same as in 1850. So that, for a period of upwards of 150 years since the new cut was made, although the promised depth of 15 feet had not been attained by a small deficiency, the navigation was benefited by the reclamation works in having a permanent channel in place of a shifting one, and an increased depth of at least 5 feet.

With regard to the effect on the lower part of the estuary from Barton Head to the bar, although from the surveys of Grenville Collins in 1684, and Mackay in 1732, it appears that the navigable channel has considerably altered its course at the lower end, being shown at that time as taking a north-easterly direction from Helbre Island along the south-east of Hoyle sand, whereas now the main channel is by Mostyn Deep, to the west of the West Hoyle Bank, a second channel going to the east of the same bank, yet the navigable depth of water is, if anything, greater than shown on those charts. The depth on the bar is not given previous to 1839, when 9 feet was shown. Rennie in 1837, and Scott-Russell in 1845, reported the depth as being 12 feet. The Admiralty chart of 1886 shows 15 feet.

The shape of the estuary of the Dee, with its gradually converging coast-lines and the great rise of tide, appear to render it eminently adapted for the propagation of the tidal wave, and for providing a good deep navigable channel at small outlay. No doubt, if the requirements of the navigation of the last

century and those of the present day be taken into consideration, the channel is now in a comparatively worse condition than it was when the reclamation works were carried out; but against this must be set the fact that no works of any importance have, since the completion of the reclamation works a century and a half ago, been carried out for improving the channel. A gradual extension of the training walls as advised by Telford and Rennie, which could have been effected at a moderate cost, would have effected a material improvement by cutting off the sharp bend above Flint, and giving the channel such a direction as would have taken it straight into Mostyn Deep. A moderate amount of dredging up the centre of the permanent channel could have been effected without disturbing the existing training walls, and would have given the statutable depth, enabling the Commissioners to take tolls and placing additional funds at their disposal.

The direction given to the channel when the reclamation works were carried out was opposed to all correct principles of river hydraulics. Kinderley was no doubt driven to this against his better judgment by some strong local influence. If the channel had been kept more in its old course on the Lancashire side, and trained with a gentle curve, instead of having a long straight reach terminating at each end in sharp curves, the scouring effect both of the tidal and fresh water would have been far more effective in maintaining deep water, and its influence on the lower reach have been much greater. Considering also the short tidal run and limited drainage area of the Dee, the low-water channel is too wide to maintain its proper depth by scour. The sharp curves in the permanent channel below Chester derange the action of the flow, and add an impediment to the scouring action. So long as they are permitted to remain in their present condition they must prevent any large vessel reaching Chester, as the sharpest bend has a radius of only 528 feet, and the two others, less than half a mile apart, of 1089 and 1650 feet respectively in a channel of 320 feet in width. In fact, the Dee is an instance of fair results obtained in spite of bad engineering and adverse tidal conditions in the higher part of the river; and of neglect by those in charge in continuing the works commenced to meet the growing requirements of the navigation. A comparison was drawn in 1818 by Telford between the Dee and the Clyde, which at that time was in

favour of the former river. The case now is of course altered; but, in comparing the Dee with either the Clyde or the Tyne, the amount of money spent must be taken into consideration. On the Dee only about £100,000 was spent, a very small portion of which was provided by the navigation authorities. The works were carried out by a company formed solely for the purpose of reclamation, with a result that the produce from about 7000 acres of land of excellent quality, formerly bare sands, has been added to the national resources.

In 1891, the Commissioners, having obtained fresh powers under an Act of Parliament, carried out a limited amount of dredging in the channel, and by this means obtained an increased depth. In the following year, after an inquiry held by Sir George Nares, R.N., for the Board of Trade, a certificate was given that the statutable depth of 15 feet had been acquired, and the Commissioners were accordingly enabled to levy tolls on the shipping for the first time. For the removal of the shoal places in the channel, Mr. Taylor, the engineer of the trust, adopted the principle of erosion, and, by stirring up the silt and sand of which they consisted by an Eroder, kept them sufficiently alive to allow of their being transported out of the channel by the ebb currents. The depth of the water was thus increased about 2 feet.

Tidal Harbour Commissioners' Report on the Dee, 1845 and 1846. Admiralty Inquiry, Dee Navigation Improvement, 1850. Reports of T. Telford, 1817–1819, 1820–1821, 1823–1826, 1828; J. Rennie, 1837; J. Scott-Russell, 1838; W. A. Provis, 1839; Stevenson, 1839; H. Robertson, 1849.

The Ribble, although a small river, has occupied a large amount of attention during the last few years, owing to the repeated applications which the Corporation of Preston found it necessary to make to Parliament for the purpose of obtaining the powers and for raising the money required for constructing a large dock, and for training and dredging the river; and also to the unusual course which was pursued of holding an inquiry by a Commission appointed by the Board of Trade under powers specially provided by a Parliamentary committee as to works already executed, and as to the practicability of obtaining access to the dock from the sea by vessels of large tonnage.

The Ribble is 82 miles in length, and drains about 880 square miles. Its source is at Ribble Head, on the moors in the Craven

district of Yorkshire, at an elevation of about 979 feet above the sea. It has several small tributaries, which join it in its course from the source to Preston. The soil of its basin is chiefly limestone, with gravel and sand at the lower end. The tidal water flows to Brockholes Bridge at spring tides, about 5 miles above Preston. Here it is stopped by a natural weir of rock running across the bed of the river. The tide also flows up the Douglas and the Yarrow for about 7 miles. Below Preston the river formerly opened out into an estuary, gradually increasing from $\frac{1}{2}$ to $1\frac{3}{4}$ mile in width at Freckleton, a distance of $3\frac{1}{2}$ miles. This portion of the estuary has nearly all been enclosed. Below Freckleton is a wide sandy estuary extending to the Irish Sea, a distance of 13 miles (see Fig. 70). Below the River Astland the estuary was originally over 2 miles wide, but it has been reduced by reclamation to $\frac{3}{4}$ mile. At the lower end, between Southport and St. Anne's, the estuary widens out to 8 miles, the increase being at the rate of about 4000 feet in a mile. The area of the estuary is 57 square miles, the whole of which is covered with sand. These sands extend out into the Irish Sea for about 4 miles beyond the coast-line, where a depth of from 3 to 4 fathoms is reached.

The Douglas or Astland joins the Ribble about 4 miles below Preston.

The earliest chart that gives the direction of the channels through the estuary is one published in 1736. The navigable channel at 2 miles south-westward of the Naze is shown as varying from $1\frac{1}{2}$ to 3 feet in depth. At this point it split into two branches, a north channel going in a westerly and north-westerly direction to the sea, and having from $\frac{1}{2}$ to 4 fathoms at the lower end. This was again split into two channels, one running parallel to the northern shore, and the other rejoining the central channel. The Gut or central channel was hardly defined. The south channel left the central channel at the bifurcation of the latter with the north channel, and took a south-westerly direction past Southport. The centre of its waterway was situated 1 mile north-west of the existing site of the Bog Hole. The depth was from 2 to 4 fathoms in the pools. The central and south channels were both used for navigation.

The next chart is that of Mackenzie, dated 1761. On this soundings are only shown on the south channel, although both the Gut and north channel are clearly defined. The maximum

sounding between Lytham and the bar outside Southport is 4 fathoms, the depth on the bar being 3 feet. The direction of the lower end of the channel was nearly due west.

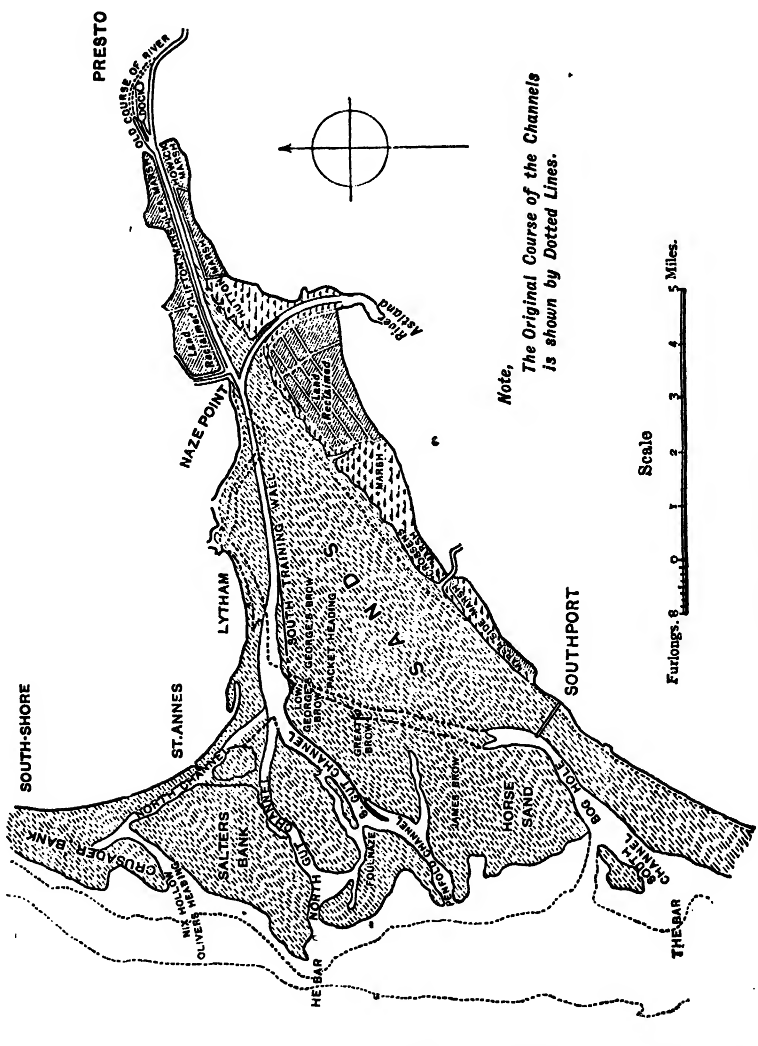


FIG. 70.—River Ribble.

"An interval of sixty-three years elapsed before the publication of Brazier's chart in 1824. In this chart the Gut or central channel is shown as the only navigable channel between Lytham and the sea, the soundings varying from about ½ to 1 fathom.

The direction of its seaward reach was west by south. The south channel had become broken up into numerous waterways. The Bog Hole had become the recipient of the drainage from the Crossens outfall, but had lost its connection with the Ribble water; its width then was 500 yards, and its depth 21½ feet. The north channel had become choked up with sand, which extended above low water from the Blackpool shore to the Gut channel.

A number of charts prepared by Parker for the use of the pilots running from 1822 to 1834 generally show two navigable channels, one by the north channel and the other by Southport, the latter having the deeper water. After 1826 the central or Gut channel is shown, but not as being buoyed out. In 1823 a plan of the estuary was made by Giles, which also shows a Gut or central channel.

The next chart is that of Belcher, of 1836. The north channel is shown as having again opened out, and the low-water Gut channel to have disappeared, and the south channel as having a wide waterway to the sea, its minimum width being 500 yards, and its minimum depth 4 feet, with 12 feet on the outer bar. The north channel appears, however, to have been the main navigable channel, the depth varying from 2 to 3½ fathoms. The direction of the seaward end was west-south-west.

From the evidence given before the Tidal Harbour Commissioners in 1845, it appears that there was then a depth of from 4 to 5 feet at low-water spring tides over the bar. The Nelson Buoy was then reported as lying in 7 fathoms, the same as it is now. The main navigable channel at that time was by the north channel and Oliver's Heading; but the Gut had existed as a navigable channel before this, and was reported then as improving. The chart of 1850 shows the training walls below Preston. The depth in the channel at high-water spring tides is given as 10 feet for the first 2 miles, and 13 feet for the next 2½ miles. Westward of the Naze, to a point 2 miles below Lytham, a high-water depth of from 21 to 27 feet is shown. The Gut channel is shown as having improved, and the Penfold channel is shown as running in a west by south direction for 2½ miles, and as having the deepest soundings, although not as the navigable channel. The north channel discharged its water by Nix's Hollow or Oliver's Heading. Its upper end was

inaccessible at low water, and the maximum depth was 4½ fathoms. The south channel is shown as no longer having any low-water connection with the Ribble. The Bog Hole had shallowed at its east end, but the depth had increased to a maximum of 43 feet and a minimum of 19 feet, with a width of 800 yards. The depth over the bar of the Gut channel was 3 feet in the shoalest place, and 6 feet over the remainder.

From the next chart, that of Calver of 1860, the Gut channel is shown as the main navigable and buoyed channel. The depth over the bar had then a minimum depth of one fathom. The Penfold channel had extended further up, and deepened and joined the Gut channel. The north channel entered the sea by Oliver's Heading in a south-west direction, and there was a depth of 7 feet on the outer bar, and only 3 feet in the shoalest part of the channel. The south channel had entirely disappeared. The Bog Hole had increased its depth to 48 feet over a diminished width of 300 feet. The water from the Crossens outfall had found its way into the Penfold channel. From a survey made for the Board of Trade Commissioners in 1890, it appears that the Gut channel shown on the chart of 1882 remains in the same position, with soundings of from 1 to 19 feet. The Penfold channel had maintained its former position with greatly increased depths. Its upper end had become shoaled by the deposit of dredgings. The junction with the Crossens channel had become enlarged. Up to the point where the dredgings had been deposited it was the deepest channel, the soundings varying from 4 feet to 4 fathoms. The north channel had continued to deteriorate, the sands at the upper end having risen 7 feet above low water. At the lower end the depth varied from 2 to 11 feet, the channel joining the sea as before by Nix's Hollow. The Bog Hole had decreased in width and length, but the depth had increased to 57 feet.

The positions of the channels in this estuary have been given in detail, as they afford an illustration of the fact alluded to in a previous chapter, of the ability of channels in sandy estuaries to maintain their position when undisturbed by artificial causes. So long as the estuary remained in its natural condition there were two principal channels, one on each side of it, a condition generally in operation in a large, wide estuary. When the shape was altered, by the enclosure of land at the upper part, and the estuary brought more to a triangular shape, the two side

channels began gradually to give place to a central channel, and this change was further aided by the training of the river for 4½ miles below Preston, and by the concentration of a larger volume of tidal water through the upper channel.

The side channel on the south has for some years past entirely disappeared, and that on the north is being rapidly filled up, being dry for a great length at low water at its upper end. The formation of the central channel has been hindered by the deposit of dredgings in the natural and immediate direction in which it was working into the main upper channel. Consequently, at present it is split into two, but both of these are better for navigation than either of the old channels, and the depth of water taken throughout in the Penfold or southern one is much greater than in either of the old channels.

The reclamation of a large area of land, and consequent exclusion of tidal water, accompanied, as it has been, by an improvement and deepening of the upper reach of the river, has not, then, in this case had the effect of injuring the navigable channel or of lessening the depth of water over the bar. On the contrary, the navigable depth throughout the lower estuary is now greater than it was formerly, and the depth over the bar, which at one time was only 3 feet in the shoalest place, is now 6 feet at low water of ordinary spring tides.

The Bog Hole also affords a remarkable example of a blind channel which maintains a great depth solely by the aid of the tidal currents. This was formerly the outfall of one of the principal branches of the Ribble channel, but for several years all connection between the Bog Hole and the Ribble has ceased. Although it has decreased in width, its depth has increased, and it has now 9 fathoms at low water.

Before the first improvements were made, vessels trading to the port had to lie at Lytham and discharge their cargoes into barges. Floods which came down the river off the moors caused very heavy freshets, causing the water to rise 12 feet, and running at the rate of 7 miles an hour. The bed of the river was 14 feet higher at Preston than at Lytham, a rise of 16 inches in the mile. A spring tide which rose 14 feet at Lytham only just reached Preston; after the upper reach of the river had been straightened and deepened, a spring tide which rose 19 feet at Lytham rose 6 feet at Preston, and a neap tide

rising 14 feet at Lytham did not reach Preston. After the removal of a ridge of rock which ran across the channel below Preston, and the construction of the training walls, the low-water level at Preston was reduced 7 feet, and the tidal range increased to 13 feet at spring tides, and 7 feet at neaps, allowing vessels drawing 14 feet to reach the quays. The propagation of the tidal wave has also advanced an hour.

The works recently carried out have still further depressed the low water, making a total increased range of 15 feet 6 inches at Preston, the range at Lytham having increased to 22 feet 8 inches, and a total increase in the advance of the tide at Preston of two hours. The first of the flood of a spring tide now takes 2 hours 12 minutes to reach from the bar to Lytham, and 2 hours from Lytham to Preston, or at the rate of 3½ miles an hour in the first reach; 3 hours 50 minutes from Lytham to Freckleton; and 4 hours 50 minutes from Freckleton to Preston. High water is 34 minutes later at Preston than at the bar, a rate of propagation of 28 miles an hour. The duration of the tide at Preston is 2 hours 27 minutes, and at Lytham 3 hours 42 minutes. This is more clearly shown on the tidal diagram, Fig. 71. The level of high water at Preston is about 6 inches higher than at the bar. The inclination of the low-water line from Preston to Freckleton is 0·70 foot per mile; from Freckleton to Lytham, 0·82 foot; and from Lytham to the bar, 0·50 foot. The reverse inclination, of the tidal line at half-flood, is 1·60 foot per mile for the upper reach, 0·94 foot for the middle, and 0·70 for the lower, diminishing at one hour before high water to 1·09 foot, 0·28 foot, and 0·24 foot in the mile.

The levels of high and low water, as adopted by the Board of Trade Commissioners, are: high water of ordinary spring tides at St. Anne's, 13·63 feet above Ordnance datum; low-water spring tides, 12·37 feet below; making the range 26 feet. At the bar the range is 1 foot 6 inches greater for an ordinary spring tide. Neap tides, 8·16 feet above Ordnance datum; low water, 6·84 feet below; making the range 15 feet. The level of the dock sill is 14·12 feet below Ordnance datum, and the crest of the bar 19 feet below.

The ordinary fresh-water daily discharge of the Ribble is estimated at 7,484,444 cubic yards, and the column of tidal water passing up and down the channel at 73,713,366 cubic yards, making the tidal water about ten times as great as the

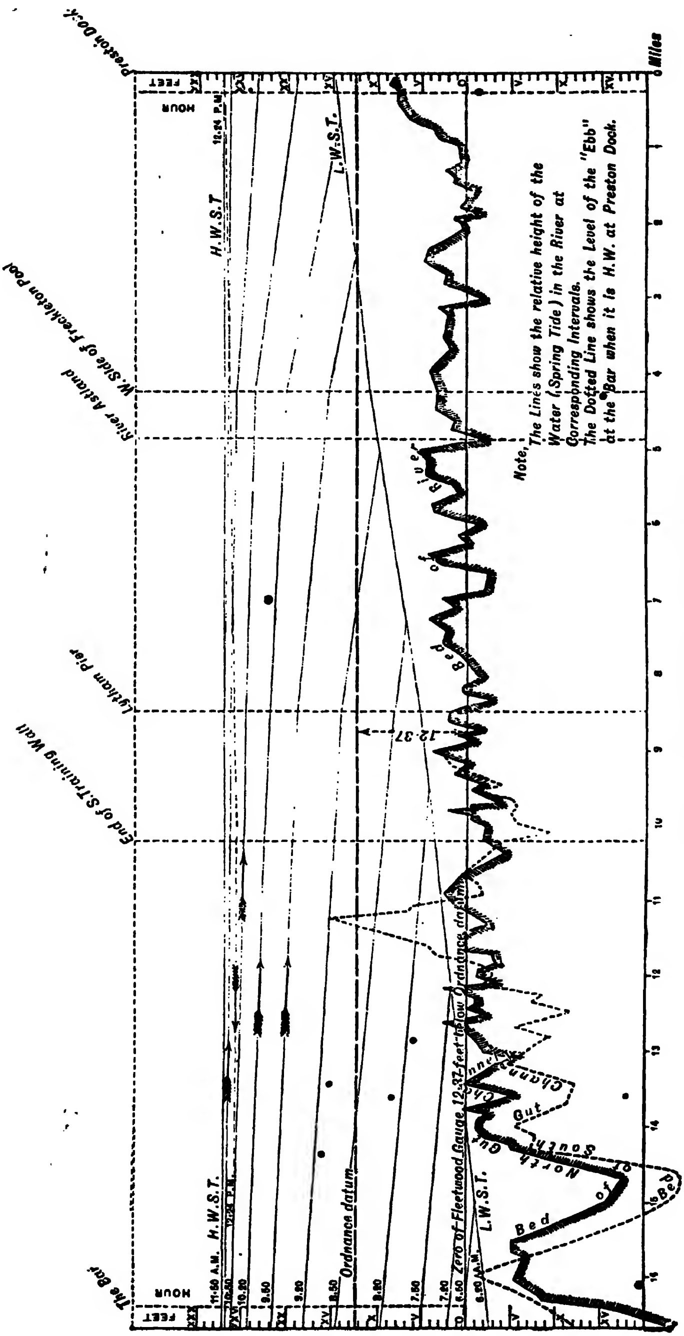


FIG. 71.—River Ribble. Tidal diagram.

fresh water. Of the tidal water, the Astland contributes about one-third of the total quantity.

In 1806 an Act was obtained by a Company of Proprietors, with power to improve and buoy the channel, and take tolls. Under their directions a number of jetties were put in between the Naze and Preston, with the object of straightening and deepening the river, and reclaiming the marsh land in this part of the estuary. The works did not prove a success, and the Company got into debt to the extent of £4000. A new company was formed in 1837, with a capital of £22,000, and further powers were obtained in 1853. Under Mr. Stevenson's direction, a dam of sandstone rock, half a mile below Preston, 300 yards long, which rose above the bed of the river from 3 to 5 feet, and containing 30,000 cubic yards, was removed by blasting and dredging; 800,000 tons of gravel were also dredged, and 7½ miles of rubble stone training walls (including both sides) put in; the cost of these works being £47,000. Quay walls were put in at Preston, and a lighthouse erected at St. Anne's.

The rock was excavated inside a coffer dam, consisting of two rows of iron rods 3 feet apart, jumped 15 inches into the sandstone rock. On the outside, three timber walings on each side were fastened to the iron rods by bolts passing through the dam, and the inside was lined with planks, the space between being filled with clay puddle. The dam was strutted with raking shores on the inside. The maximum head against the dam was 16 feet; the depth of the rock excavated, 13 feet 6 inches.

The training walls were put in, having their top about 4 feet above the then low-water mark, and 300 feet wide at the top, increasing to 370 feet at the lower end. These walls only extended as far as the Naze, 4½ miles below Preston. Any further extension was opposed by the landowners on both sides of the estuary, on the ground that such extension might have an injurious effect in diverting the water from the southern course across the sands, and so ultimately lead to the silting up of Bog Hole, which gives the only water in front of Southport at low tide; and by those on the north side, on the ground of injury to the north channel.

The effect of these works was to depress the low-water level 6 feet 8 inches at Preston, and advance the arrival of the tide one hour, and, by thus giving a greater range of tide, allowing

vessels of from 12 to 13 feet draught to reach the quay during spring tides. The tonnage of the port did not by any means increase in proportion to that of the size of the town, the tonnage in 1882 being returned as 28,000 tons.

In 1882 the Corporation of Preston, who had a large interest in the Navigation Company, obtained, on the strength of a report made by Sir J. Coode, Parliamentary powers to purchase the whole of the rights of the Ribble Navigation, for the sum of £72,500, which included a large tract of reclaimed land, the navigation rights alone being put at £18,759. They were also authorized by the Act to construct a dock of 36 acres at Preston, and to dredge the channel between Lytham and Preston, so as to give a depth up to the dock at high-water spring tides sufficient for large steamers; and to extend the training walls 3½ miles further into the estuary. The amount authorized to be borrowed for these works was £650,000. Subsequently the size of the dock was increased to 40 acres, a tidal basin of 4¾ acres was added, and the sill made 2 feet 6 inches lower than in the original design. It was also intended to dredge the river 18 inches deeper than the first scheme. These additional works added to the original estimate a further sum of £510,000. The sum authorized to be expended, under Acts obtained in 1888, 1889, and 1890, was, however, only £321,000.

The contract for the dock, river diversion, and training walls was taken by Mr. James Walker for £456,000. The engineers for the Corporation were Messrs. Garlick and Sykes, who had previously acted for the Company of Proprietors. Sir John Coode prepared the Parliamentary plans, and supported the scheme in Committee. The works were afterwards taken charge of by Mr. Benjamin Sykes, and were carried out to completion by him, the dock being opened in 1892.

The dredging was carried out by the Corporation under the direction of Mr. Sykes. Two powerful dredgers, each capable of raising 300 tons of boulder clay an hour, with barges and tugs, were purchased at a cost of £37,068 for the two dredgers, and £46,672 for the two tugs and twelve barges. The training wall on the south side was extended to about a mile below Lytham, the stone excavated from the dock being used for the purpose. The north wall has also been extended to some distance below the mouth of the Astland. The top of the old walls was made 15 feet above Ordnance datum at Preston, and

10 feet at the Naze. The continuation of the walls has been carried on, commencing at the same height, and lowering to the level of Ordnance datum at the termination below Lytham. Low water of spring tides is 3 feet below Ordnance datum at the Naze, and 10 feet below at the end of the walls; neap tides are 8 feet above datum. The top of the walls is thus 13 feet above low water and 2 feet above neap tide level at the Naze, and 10 feet above low water and 8 feet below neap tide level at the termination. The walls are 300 feet apart at the top near the dock, and 370 feet at the Astland, a rate of divergence of 20 feet in a mile. Under the Act of 1883, it was intended to dredge the river down to the level of the dock sill as then shown. Subsequently it was proposed to lower it 2 feet more, so as to bring it to the level of the sill as now laid, with an inclination at the rate of 3 inches in the mile, the width at the bottom to be 300 feet. The total quantity of material to be removed was 3,611,600 cubic yards, including 20,000 yards of rock, and 1¾ millions of hard marl and boulder clay. It was estimated that two-thirds of the sand overlying the clay and between the high hard ridges, amounting to 2¾ million yards, would scour away as the clay bars were removed. The cost was estimated at £232,497, or about 12·87*d.* per yard.

The dredging was commenced at the increased depth, but the line has since been raised to the original level of 1883, and the width diminished to 200 feet.

Very considerable opposition having arisen as to the large increase of expenditure over the original estimate, and statements having been made that when the dock was completed it would be impossible to maintain a navigable waterway to the sea of sufficient depth for large steamers, the matter, after being fought out before the Parliamentary Committees of three sessions, was finally referred for report to a Commission appointed by the Board of Trade, consisting of Sir George Nares, Sir Charles Hartley, and Mr. Wolfe Barry. The main question in dispute was as to the practicability of maintaining a deep-water channel from Preston to the sea, this being further complicated by conflicting opinions as to which of the three existing courses should be adopted as the navigable channel. Sir John Coode, when he prepared the original Parliamentary plans, selected the central or Gut channel as the course to be improved. Subsequently Mr. James Abernethy, who was called to advise as between the

Corporation and their opponents, advised the adoption of the north channel, following the line of the present channel past St. Anne's, but, instead of joining the Irish Sea by means of Oliver's Heading, continuing in a north-westerly direction through the Crusader Bank past South Shore and Blackpool. The Corporation of Southport contended for the opening out of the channel which formerly ran on the south side of the estuary and joined the Irish Sea through the deep gut known as the Bog Hole. Their contention was supported by Mr. Vernon-Harcourt; the central or Gut channel was supported by the local engineers, Messrs. Garlick and Sykes, Mr. Alfred Giles, Sir James Brunlees, Sir A. Rendel, Mr. Deas, the engineer of the Clyde, the late Mr. J. Fowler, the engineer of the Tees, and the author. It was contended by the engineers advising the Corporation that a careful study of the natural causes operating in the estuary showed that, while this channel had for many years past been improving, the other channels had been deteriorating—it was therefore fair to conclude that it would be easier to maintain deep water along this course; that the approach from the sea into a north channel so near a lee shore as designed by Mr. Abernethy would be very dangerous, vessels entering being exposed to a beam wind during heavy gales from the south-west, the prevailing wind on the coast; that the outfall would require a large amount of dredging to give sufficient depth, a slow and difficult operation in such an exposed situation; that when made it would be difficult to maintain deep water there, as its direction was opposed to the natural set of the currents; that the tide on this part of the coast, coming from the south-west, sets directly into the estuary of the Ribble, and the several outfalls of the channels all trend in that direction, or nearly opposite to that selected for the outfall of the north channel; that the littoral drift of sand and shingle has a tendency to accumulate in the direction of the strongest gales and the set of the tides, and, being here stopped by the coast-line, would tend to drift into and form across the mouth of this north channel; that the north channel from Lytham to St. Anne's had also been shoaling for several years, the depth having diminished from 6 and 7 fathoms to 2; and that it would be dependent solely on the scour obtainable from only one side of the estuary. The advantages claimed for the north channel were, that it would be sheltered on the north and east sides

for part of its length by the St. Anne's shore, and to about half-tide level on the seaward side by the Salthouse bank; that for a length of 2½ miles only one training wall would be required; that the substratum would be more favourable to the construction of the training walls. The south channel having become entirely silted up, it was contended that the expense of reopening it would be very great, and that the cost of making and maintaining the walls would be very costly, without any corresponding advantage except a problematical one to Southport. This Corporation, also, were not prepared to contribute towards the extra cost of taking the channel in this direction.

The Commissioners appointed by the Board of Trade in 1888 made an interim report in 1889, and their final report in 1891. The conclusions at which they arrived may be thus summarized. After dealing with the advantages and disadvantages of the north channel, they point out that if such a channel were carried out, the direction would have to be in a more westerly direction than that laid down by Mr. Abernethy; that this would involve double training walls and the extension to deep water, the channel to follow a curve of 6 miles radius from 8½ to 13 miles below Preston, and thence a curve of double that radius to the sea, the width of the navigable channel below Lytham to be 450 feet, and the width between the walls 800 feet at Lytham and 1850 feet at the sea entrance, the widening out being calculated at the rate of 150 feet per mile. Taking into consideration, therefore, the cost and the serious drawbacks inherent to this channel, they came to the conclusion that they could not recommend the adoption of a waterway along the north shore. Three alternate schemes for forming a south channel were considered, the difference being in the point where the new channel should leave the present training walls. The one to which attention was specially directed was a channel leaving the present course at the eighth mile below Preston, with a curve of 6 miles in length and 4 miles radius extending to the Bog Hole, involving a curve of contrary flexure at the Bog Hole, having a radius of only ¾ of a mile, and requiring the extension of the wall below Southport in order to keep the channel in its place. The advantages due to this course were that the sea outlet is more stable than either the Gut or north channel; that the outer portion of the channel, 4 miles in length, is maintained by natural means; that there is deep water

anchorage in Bog Hole. The disadvantages: that the course from Preston to the sea would be 3 miles longer than by the central channel; that the sharp curve at the junction with the Bog Hole was very objectionable; the difficulty of constructing and maintaining training walls across the set of the tides in the estuary, and the necessity of raising the wall on the upper side above high-water mark, to prevent the tides setting across the channel and encouraging the deposit of sand; the greater depth at which the hard material lies below the surface, involving a greater cost in construction of the walls; and the great cost of constructing and maintaining the walls, and also of dredging out a new channel. In the opinion of the Commissioners, the objections so far outweighed the advantages that they were unable to recommend the adoption of this course.

They therefore advised the central course by the Gut channel as the one to be adopted. They further advised that the two training walls should be extended from Lytham to the fourteenth mile below Preston, the distance between the walls at the ninth mile to be 800 feet, widening to 1550 feet at the fourteenth mile, or at the rate of 150 feet per mile. The estimated cost of this work was put at £220,000, including the removal by dredging of such of the material as was not taken away by scour. The depth of water when this work was completed was estimated at 26½ feet at ordinary high water of spring tides at the fourteenth mile, or 3 feet more than at the present time. This was advised only as a tentative proceeding, the full extension of the walls out beyond the bar being contemplated as a work to be carried out at some future time. The cost of this lower portion of the work, owing to its exposed position, would be very heavy, being estimated at £372,000.

The Gut channel was probably selected by the Commissioners as being the present buoyed and navigable course, and as being in the direction contemplated by Sir John Coode when he laid out the line of the training walls. The Penfold channel has, however, the deeper water, and its direction seems to coincide more with the natural set of the tidal currents, and, having a slightly curved form, it appears to be in a better form to maintain permanently deep water than the straight course of the Gut. If the few shoals of sand between the deep pools along the Penfold were opened out, and the obstruction at the

top end removed, there is every reason to suppose that a good navigable channel could be opened out and maintained along this course with a comparatively small amount of sand-pump dredging, and without the aid of training walls.

As the Corporation failed to obtain the necessary powers and money to deepen the river to the increased depth to which the sill of the dock was laid, the bed of the river, when the present works are completed, will be 3 feet above the sill, and, as the material of which the upper part of the channel is composed is hard boulder clay, there is no chance of any improvement by scour. The depth of the river when the present works are completed will be 5 feet less than was contemplated when the Act of 1883 was obtained. To extend the training walls to the fourteenth mile will also require further Parliamentary powers.

The present available depth from the dock to the bar is 22½ feet at ordinary spring tides, and 12½ at neap tides.

The channel is lighted with gas-buoys, the outer or Nelson buoy being made an occulting light.

Report and Evidence of the Tidal Harbour Commission, 1847. Reports of Captain Belcher, 1836; R. Stevenson and Son, March and May, 1837; Bell and Miller, 1866; Sir J. Coode, 1882; J. Abernethy, 1888. Report of the Ribble Navigation Commission to the Board of Trade, 1891 (including the interim report).

The Witham.—The Witham has been selected as an example of a tidal river that has been improved and trained by means of fascine-work, and also on account of the disturbance of its tidal conditions by the erection of a sluice across it.

The Witham is 89 miles in length, and drains 1063 square miles. The tidal flow only extends to Boston (see Fig. 72), about 8 miles above the outfall. The tide flows here from 2½ to 3 hours, and springs rise about 20 feet at Boston and 22 feet at the outfall. The river above the tidal portion is canalized to Lincoln, whence it joins the Trent by means of the Fosdyke Canal. This river at one time held an important place in the navigation of the country, when the chief over-sea trade was with the Netherlands, and Boston, with other ports on the East Coast, were the chief places of export and import.

In the middle of the last century the landowners, in order to reclaim a large tract of fenland lying between Boston and Lincoln, obtained an Act of Parliament empowering them to straighten

and improve the river above Boston, and at the same time to erect across it a large sluice with self-acting doors, which closed on the flood tide, and opened again as it receded to discharge the land water. By this means the flow of the tide was entirely stopped at this point. The rise of a spring tide above the sill of this sluice is 16½ feet. The portion of the river below the

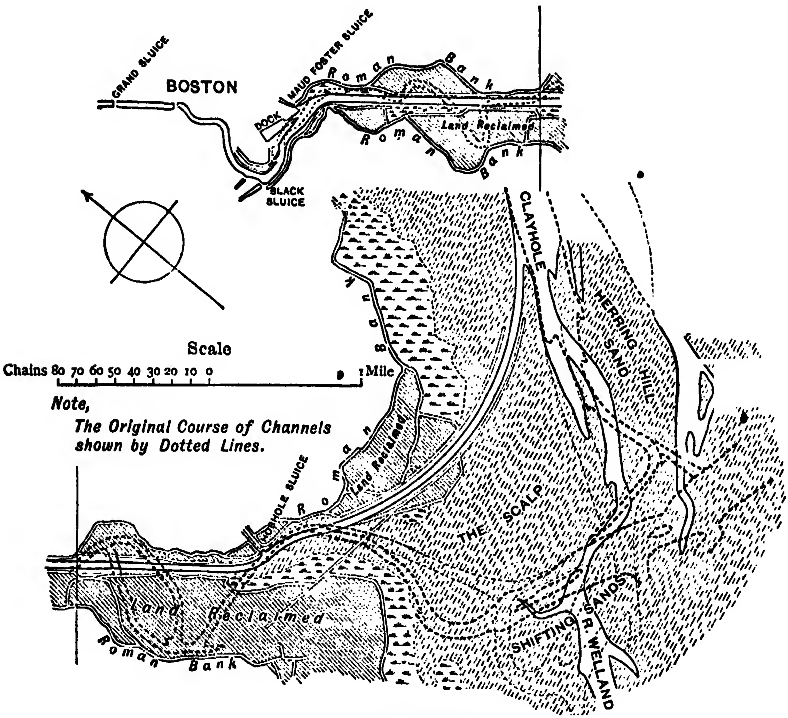


FIG. 72.—River Witham.

town pursued a very winding course between salt marshes, and at the lower end through a large bed of silt and sand, where it was joined by the Welland, and with it, after a devious and uncertain course, reached the deep water of the estuary.

The river below Boston is under the jurisdiction of the Corporation of Boston, under a charter granted in Queen Elizabeth's reign.

In the end of the last century Captain Huddart was consulted as to the best means of improving this channel for the navigation, and advised its diversion by a new cut at the lower

end, so as to avoid the shifting sands. Subsequently Mr. Rennie reported more fully, and advised the straightening and improving the whole of the channel from Boston to the sea; and also recommended a new outfall, much on the same lines as proposed by Captain Huddart. Subsequently the Corporation obtained the necessary power from Parliament to carry out the works, except the new cut. The river was straightened by training it with fascine-work through the salt marshes, two short cuts being made through old land where the soil was clay. The fascine-work was executed by Mr. Beasley, who carried out similar training works in the adjoining river Welland, this being the first example of this kind of training carried out in this country. The material of which the marshes was composed was entirely alluvial matter which had been brought down the river in floods, and was easily scoured away by the current. No dredging was therefore employed to excavate the ground along the new course of the channel, but it was entirely removed by scour as the work progressed. The method of proceeding was as follows: The line of the new channel was set out, commencing at the existing channel, and proceeding in a direct line across the marshes to where the channel again crossed at the next bend, the largest interval between the bends being about one mile. The fascine-work was commenced at the upper end, at the concave bank of the old channel, working out towards the channel. As soon as the contraction began to be felt, the material, being silt, scoured away from the opposite or convex side very rapidly. The fascine wall on the other side was then commenced, and gradually pushed on; and so both sides were continued until a new channel was scoured out along the intended line. The fascine-work consisted of thorn faggots, about 6 feet long and 3 feet girth, the brush being all placed at one end. They were laid overlapping each other at right angles to the channel, with a batter of about $\frac{1}{2}$ to 1. On each layer of fascines was placed a layer of sods obtained off the marsh. The work was carried up to half-tide level. The cost of this fascine-work was about £21,500; and of the cuts through the old land and other works of improvement, £21,000. This straightening of the river extended as far as a place called Hobhole, about three miles, beyond which the channel still continued to work its way through the sands. The river was very greatly improved by these works, and made navigable for

vessels of 300 tons. Larger vessels remained in the roadstead, and discharged into lighters.

The course of the channel through the sands was very devious, continually altering as the upland or tidal water had the greater influence, heavy freshets frequently causing a new direction to be taken. During this process an enormous mass of sand and silt was turned over, the sides of the channel in places forming a steep 10 or 12 feet high, large masses of silt continually falling down into the channel. When the winter rains had ceased, the flood tide again began to assume the mastery, and to seek its old course, repeating the process. During this operation the river became charged with the disturbed silt, and carried it up with it partly in suspension, but chiefly by driving it up along the bottom of the channel in a state of semi-flotation. When the tide was checked at the Grand Sluice it rebounded, meeting the succeeding wave and causing an eddy and slack water. After high tide the water gradually subsided there, owing to there being no run of ebb. There being no downward current at the upper end to carry the silt back, it remained behind, and gradually accumulated, the quantity ultimately deposited depending on the amount of rain and the quantity of fresh water coming down the river. In very dry seasons the river-bed became raised as much as 11 feet at the Grand Sluice, gradually tailing off, but raising the bed of the river the whole way down. Under such circumstances neap tides could barely reach the quays, and the navigation was seriously impeded. With continued heavy winter freshets, the whole channel would be scoured out down to the hard clay; but as the upper part of the river improved the lower part became worse, owing to the consequent shifting of the channel through the sands. The author calculated that the quantity of silt thus brought into and scoured out of the river in one season amounted to over 1½ million tons.

The question of improving the outfall continued to occupy the attention of both the harbour and drainage authorities from time to time, and reports were obtained from several engineers. The general tenor of these reports was to the effect that the obstruction of the tidal flow by the Grand Sluice was detrimental to the outfall of the river, and advising the construction of a new cut at the lower end, so as to avoid the sands.

In 1837 Sir John Rennie, in accordance with instructions received from a meeting of landowners and others interested in the fen rivers, brought forward a scheme for training by fascine-work the Ouse, the Nene, the Welland, and the Witham in one common outfall in the centre of the Wash, and the enclosure of 150,000 acres of land. At a meeting held in London, of which Lord George Bentinck was chairman, it was decided that it was desirable that this scheme should be carried out, but that, as the cost of its execution exceeded the means of private individuals, it ought to receive the consideration and support of the Government as a national object. Subsequently the scheme was partially revived, and the Lincolnshire Estuary Company obtained Parliamentary powers to train the Witham and the Welland to Boston Deeps, and to enclose 30,000 acres of land. The scheme, however, was found impracticable, and the powers obtained were allowed to lapse.

In 1860 the Drainage Commissioners obtained a report from their engineer, Mr. W. Lewin, as to the best means of obtaining relief from the flooded condition of the lower lands in wet seasons. Mr. Lewin advised that no permanent improvement could be obtained unless the outfall of the river was improved, and advised the carrying out of Mr. Rennie's scheme for making a new cut across the marshes to Clayhole, giving details and estimates of the proposed work. Subsequently Sir John Hawkshaw was consulted by both the Harbour Commissioners and Drainage Trustees, and he endorsed Mr. Lewin's recommendations. The difficulty of deciding as to the proportion of taxation to be imposed on the lands to be benefited, and the amount to be found by the different trusts interested, prevented any action being taken.

The Harbour Commissioners then instructed the author to advise as to whether the channel could not be improved for navigation at a cost within the resources of the Corporation. Accordingly, in a report dated October, 1870, the author advised the fixing the channel in one position by continuing the fascine training from Hobhole to Clayhole, a distance of $3\frac{1}{2}$ miles, and the removal by dredging of the hard shoals, leaving the silt to be removed by scour, as had been done in the upper part of the river. The estimated cost of this scheme was £21,000. The advantage of this *training of the natural channel* over a direct cut was that, instead of carrying the Witham away from

the Welland, the two rivers would continue to be united, and jointly assist in maintaining a common outfall; and that it could have been carried out without obtaining additional Parliamentary powers. The disadvantage was that the length of the course from Hobhole to Clayhole would be $1\frac{1}{4}$ mile longer than by the proposed cut. As, however, a greater width of channel was to be given than by the proposed cut, the discharging power in times of flood would have been greater, and the fall in the surface less. The level at Hobhole in both cases would therefore have been practically the same.

The Harbour Commissioners approved the scheme, and expressed their willingness to carry it out if the drainage authorities would contribute a fair sum towards the cost.

A long succession of wet seasons finally brought matters to a crisis. At a meeting of representatives of all the Trusts interested it was finally determined to proceed with the improvement of the river. The two schemes were submitted, and it was decided to proceed with the larger one. The details of the scheme were settled by the two engineers representing the principal Drainage Trusts and by the author on behalf of the Harbour Trustees. The contribution of the latter was fixed by the representatives of the Trusts at a moiety of the cost of the training which the Harbour Trustees had been willing to carry out. Powers were obtained from Parliament in 1880 constituting an Outfall Board representing the different Trusts, and for carrying out the work; for raising £150,000, the estimated cost; and for taxing the lands benefited for paying the interest on the outlay and the sinking fund. The bill was opposed by the Commissioners of the river Welland, on the ground that the separation of the rivers would be injurious to their outfall. The objection was met by the insertion of a clause by which the Outfall Board undertook to contribute towards the cost of training the Welland from the old junction to the outfall of the new cut, if required to do so.

The carrying out of the work was placed in the hands of Mr. J. E. Williams, the engineer of the Witham Commissioners, the largest contributing body, the author, as representing the Harbour Commissioners, and Mr. James Lancaster, the engineer of the other contributing Drainage Trust, being associated with him.

The new channel consists of a cut made across the enclosed marshes 1 mile in length, and across the open marshes for

$1\frac{1}{4}$ mile. The old channel above this was dredged by the Outfall Board to a depth sufficient for drainage purposes, and was subsequently deepened by the Harbour Trust to the level of the sill of Boston Dock.

The channel is curvilinear in plan, having a radius of 8500 feet. The average bottom width is 100 feet at the upper end, and 130 feet at the lower, with slopes of $4\frac{1}{2}$ to 1, and a foreland or berm 60 feet wide. This small rate of increase was given to the channel in consideration of the short distance of the tidal run; but the current is greater than is desirable, and the banks, except where they consist of clay, have had to be protected with fascine-work, partly on account of the current, and also from the effect of the wash caused by the steamboats. The depth of the water in the channel at Clayhole is $27\frac{1}{2}$ feet at high water of spring tides, and $20\frac{1}{2}$ feet at neap tides. The excavation through the enclosed land was 23 feet deep and 300 feet wide at ground level, the soil consisting of silt and clay, and hard boulder clay at the bottom. The total quantity of excavation was two million cubic yards, which was effected by three steam-excavators, which advanced nearly abreast, the spoil being deposited on banks run out at the lower end of the channel. The contract for the work was taken by Mr. James Monk for £96,052, the price for the excavation as measured from the sections being 1*s.* per cubic yard, which included the construction of a bank across the old channel and a considerable amount of dredging at the lower end.

Since the new outfall has been completed the silting up of the channel has ceased, and the river is now navigable for vessels of 2000 tons at spring tides. The advantage to the drainage has been the depression of the low-water level 6 feet 6 inches at the lowest outfall sluice, and 4 feet at the Grand Sluice and Black Sluice.

The improvement of the river enabling a much larger class of vessels to navigate it, the Corporation of Boston obtained an Act in 1881 giving them power to construct a wet dock near the town, and the works were carried out, from plans prepared by the author and under his direction, Mr. James Abernethy acting as consulting engineer, by Mr. W. Rigby as contractor, at a cost for the dock, hydraulic machinery, and warehouses of about £150,000.

Reports on Boston Haven, Captain Huddart, 1793; J.

Rennie, 1800, 1822, 1823; T. Telford, 1823; J. Rennie, 1841; W. Lewin, 1860; J. Hawkshaw, 1864; W. H. Wheeler, 1870. "Description of the River Witham and its Estuary," W. H. Wheeler, *Mem. Proc. Inst. C.E.*, vol. xxviii.; "The Conservancy of Rivers in the Eastern Midland District of England," W. H. Wheeler, vol. lxvii.; "The Witham New Outfall Channel and Improvement Works," J. E. Williams, vol. xcv.

The Seine.—The Seine affords a striking instance of the advantage to be obtained in a tidal river by works confined to the regulation and training of the channel. The improvements

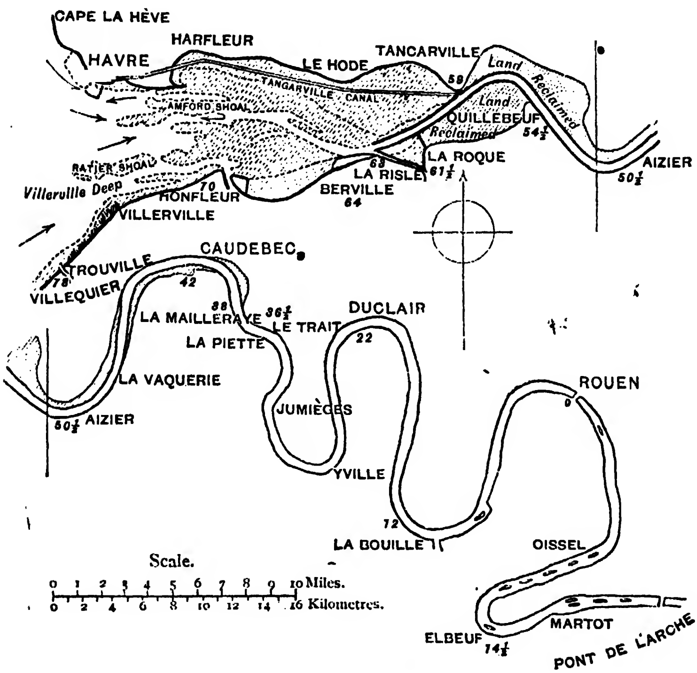


FIG. 73.—River Seine.

which have been effected in this river are the result almost entirely of training and the consequent scour. Dredging has been used to a very limited extent, for the purpose of removing a few hard shoals and deepening the harbour at Rouen.

Rouen is situated 76 miles from the sea by the course of the river (see Fig. 73). Forty years ago the navigation to this port was restricted to vessels of 200 tons, drawing about 10 feet of water. For about half the course the channel was shallow and

shifting, winding through an estuary encumbered with shoals on which there was not more than 10 feet at high water, and on some less than 2 feet at low water; the rest of the course was through a fixed channel. The depth at Rouen at low water was only about 2½ feet. Since the training works have been completed, the navigable depth up to Rouen has been increased to 17⅓ feet at neap tides, and 20⅓ feet at ordinary spring tides. Twenty years ago the area of the maritime basin of the port of Rouen was limited to 37 acres, and the length of quays did not exceed 2187 yards. In the centre of the river the depth of low water reached 19 feet, but nowhere alongside the quays was it more than 13 feet. Although the training walls were then nearly completed, and the increased scouring force was rapidly deepening the river-bed, there were at many points shoals which formed serious obstructions to its navigation. At the present day the area of the port has been increased to 59¼ acres, over which the depth at low water in parts reaches 32·80 feet, and nowhere is less than 19 feet alongside the quays. The low-water depth, formerly 13 feet, now varies from 19 feet to 22·58 feet. The length of quays has been increased to 5337 yards. In 1891 2130 vessels entered the port, of which 80 were of 19·66 feet draught and above, and 455 between 19·66 feet and 16·42 feet draught. The largest vessel which has entered the port carried a cargo of 3600 tons. The total tonnage entering the port was 1,763,131 tons. A larger number of British ships now enter the port of Rouen than that of Bordeaux. The canalized portion of the Seine between Rouen and Paris has had the water deepened, so that barges carrying from 800 to 1000 tons are now able to reach Paris, and steamers of 300 tons burden trade regularly between London and that city.

The immense advantage to the commerce of France in having ocean-going steamers penetrating fifty miles into the interior of the country, and communicating with Paris and a very large area of country beyond by means of the canals, is due to engineering skill applied in regulating and training a tidal river and developing its natural resources.

The Seine is 480 miles long, and drains 30,370 square miles of country. It is navigable for 350 miles from its mouth. In its natural condition the tide flowed as far as Pont de L'Arche, 19 miles above Rouen, but it is now arrested by the locks at Martot, near Elbœuf, 15½ miles above Rouen, making the tidal

run 93 miles from the sea, and 79 miles from the lower end of the fixed channel in the estuary. The average discharge of water is estimated at 634 cubic yards a second, the low-water discharge being 340 cubic yards, and the maximum in floods 3270 yards.

The quantity of sediment brought down by this river is small, and contrasts strongly in this respect with some of the other rivers in France. The fall in the surface of the water at spring ebbs below Caudebec varies from 0·31 foot to 0·41 foot per mile.

The distance from Paris to the sea in a direct line is 115 miles, but by the channel of the river 226 miles. From Rouen to the sea the direct distance is 45 miles, and by the channel 76 miles. Neap tides rise 18 feet, and spring tides rise 23 feet at Havre, and 6 feet 7 inches at Rouen.

Several schemes have been proposed since the middle of the last century for improving the navigation of the Seine, including a canal for avoiding the estuary, and training works.

The canalization of the upper part was accomplished in 1838. The size of the locks and the depth of water on the part between Martot and Paris was increased in 1878 to 520 feet in length, 39½ feet in width, and 10½ feet in depth.

In 1845 M. Bouncieau submitted a plan for improving the Seine from Rouen to the estuary by means of training walls. This scheme was approved and adopted, and the works commenced in the following year, but have not been extended as far as originally intended. The works were at first confined to the part of the river between Villequier and Quillebeuf, a distance of 10 miles. The result of this training was so satisfactory, the depth of the water over the shoals being increased from 10½ to 21 feet at high-water spring tides, that a further extension was authorized, and the training was ultimately carried up to La Mailleraye and down to Berville. A shoal of hard ground at Meules Bank was also dredged away. The works were completed in 1869. The training extended over a length of 26½ miles, the length of the training walls amounting to about 45 miles. The width of the channel was made—

Miles.		Feet.
0	at Rouen	500
37½	at Mailleraye	820
59	at Tancarville	1640
63	end of training walls	2296

The walls were made of rubble chalk, obtained from cliffs adjacent to the river. The chalk was tipped into the channel along the line of the intended training wall, and levelled to an even face above low water. The top was made 6½ feet wide, with slopes of 1 to 1 on the land side, and varying on the river side from 1½ to 8 to 1 according to the force of the current. The walls were raised to high-water level down to La Roque; below this they were at first only raised a few feet above low water, but subsequently it was found necessary to increase the height, as the tide, rising over the top of the banks, washed the material away and injured them.

The velocity of the tidal current did so much damage to some parts of the rubble walls that it became necessary to protect the toe with sheet piling, and the upper part with an apron of concrete about a foot thick.

The chalk cost an average of 1s. 0½*d.* per cubic yard in the bank.

The material of which the upper estuary was composed consisted almost entirely of sand or alluvial matter, and when the current became confined and concentrated by the training walls, this was scoured out of the channel by the ebb current. The quantity thus removed was estimated at 80 million cubic yards.

A considerable accumulation of alluvial matter became deposited at the back of the walls, 25,000 acres of which became fit for reclamation and were enclosed.

During the past ten years dredging operations have been carried out for removing the hard shoals below Rouen. The longest shoal was at Bardonville, about 19 miles below the town. This shoal was 2 miles in length, over which a depth of only 17·70 feet was to be found at high water of neap tides. A fairway was dredged, 328 feet wide, over which there is 23 feet at ordinary high water. The depth throughout in the shoalest places in the river at ordinary high water is 20·30 feet, and at high springs 26·25 feet.

The effect of the training on the channel of the river was to lower the bed an average of 8 feet over 27 miles; to lower the line of low water at Rouen 2 feet 3 inches at spring tides, and 2 feet 9 inches at neap tides. The high-water line at Rouen remains unaltered, and is nearly the same as that at Havre. The tides reach Rouen an hour earlier than before,

and high water is now $5\frac{1}{4}$ hours after high water at Havre. The tidal wave on the first of flood travels from Honfleur to Rouen in 4 hours and 20 minutes, and the first of the flood reaches Rouen $2\frac{1}{4}$ hours after high water at Havre.

The average rate of propagation at low water is thus a little over 16 miles an hour; but the rate varies in different parts of the river, being about 7 miles an hour over the first 7 miles, 18 miles an hour over the next $20\frac{1}{2}$ miles, 25 miles an hour over the section between Caudebec and Duclair, where the river is 20 feet deep, and 17 miles an hour over the upper reach to Rouen.

The tidal effect has reached beyond the limit of the training walls, as the time of high water at Havre is advanced 38 minutes. Spring tides rise 23 feet at the mouth of the estuary, 10 feet at St. Mailleraye, and 6 feet 6 inches at Rouen.

The results indicate that the training walls have not been sufficiently expanded, and are too close together to allow of a free entrance for the tidal water. This is shown by the confusion of the tidal flood current coming up the estuary, part of which is driven back towards Havre, and also by the velocity with which the tidal current runs up the trained channel, advancing with a head or bore of about $5\frac{1}{2}$ feet, reaching in very high spring tides to 11 feet.

The velocity of the tidal current is a source of considerable danger to the navigation. A large English steamer, the *Romeo*, 300 feet long and 36 feet beam, was wrecked by the bore, on the Villequier sands.

If the walls had been placed a greater distance apart, the flood would have led in more gently, which would not only have been an advantage, but have considerably decreased the cost of construction and maintenance. This fact has been fully realized by the French engineers, and it has been proposed to set the walls further back at the lower end, and ease the curve at Quillebeuf.

There are eleven principal curves between the estuary and Rouen, four of which describe 180 degrees. The sharpest curve in the trained channel is between Quillebeuf and Tancarville. This has a radius of 8200 feet, and, owing to the velocity of the current round it, which attains 8·20 feet a second, is a source of inconvenience to the navigation. The sharpest curve above this has a radius of 6562 feet. Owing to the width of the river,

never less than 300 feet, and in some places 1100, the other curves do not seriously impede the navigation. The course round the bend at Duclair is 11 miles, whereas in a straight line it would only be 2 miles. Owing to the height of the land at the side of the river where several of these curves occur, it is not practicable to straighten the channel; but if the training walls at Quillebeuf had been carried in a more direct line, the curve would have been more easy, and a better approach given from the estuary.

The cost of the training walls as originally completed down to Berville was £678,000, or at the rate of £8·10 per running yard. The subsequent works of reconstruction, protection, and maintenance cost £520,000, making the total cost £1,198,000, or £15·10 per yard run. The value of the land reclaimed was £852,000, leaving the net cost of the works £346,000.

The lower estuary extending from the end of the training walls at Berville to a line drawn from Cape La Hève to Trouville, is 14 miles in length, the width increasing from about 2½ miles to 7 miles. The greater part of this space is covered with sands, through which the main channel frequently shifts its course, sometimes passing to the north of the Amford shoal by Havre, but the main direction being through the centre of the estuary, between the Amford shoal on the north and the Ratier shoal on the south. The flood tide enters the estuary from two directions, one current coming round by Cape La Hève on the north, and the other through Villerville Deeps on the Calvados coast. These two currents meet in the middle of the estuary. The main current then sets up the Seine; but there is a back current which sets downwards past Havre, causing eddies which no doubt account for the large accumulation of sand which blocks the entrance to the harbour. This entrance can only be maintained at a depth of 26 feet at spring tides by constant dredging, and the entrance for large vessels is restricted to high water. There is, however, a compensating advantage in the duration of high water, allowing the dock gates to remain open for nearly three hours. The period during which high water remains stationary is about one hour; for another hour the level only varies from 3 to 4 inches. The tide only rises and falls 13 inches during three hours. Thus spring tides flow for 3½ hours, remain practically stationary for 2½ hours, and ebb 6½ hours. This period of still water is caused by a second tidal wave

following on the first, which bends into the bay and strikes the Cotentin peninsula, travelling afterwards along the coast of Calvados as far as Havre, and prolonging the action of the first tidal wave.

The variation in height between spring and neap tides is also greater than in other rivers, the rise of springs being 23 feet, and of neaps barely 10 feet.

The set of the tidal currents in the bay is east and west, and there is a long interval of slack tide at low water. In front of Havre there is also a sharp north and south littoral current, which begins to make itself felt a little before full tide, the currents thus making the full turn of the compass. The velocity at high spring tides is from 3 to 4 knots.

The effect of the training works on the lower estuary has been the subject of some controversy. It has been contended that, owing to the curtailment of the tidal reservoir by the land enclosed, the deposit of sand has increased, and that this may ultimately have an injurious effect on the scouring action of the tidal water in maintaining the sea channels.

On the other hand, it has been shown that although, according to the surveys made, there was an apparent decrease in the capacity of the estuary from the completion of the work in 1859 to 1875 to the extent of 272 million cubic yards, or at the rate of 17 million cubic yards a year, yet the decrease after this for the next five years was 40 millions, or a rate only half as great as that which had previously been going on.

It was further shown by M. Lavoinne that thirty years ago the capacity of the estuary was less than in 1880, and that it had increased 11 million cubic yards between those periods. The channel also seawards of Havre has deepened considerably.

A portion of the decrease of the water-space of the estuary is due to the partial filling up of some of the deepest pools, a result which affects neither the scouring action nor the navigation.

It is further contended that all sandy estuaries are subject to constant changes due to storms and other causes, and surveys made of the cubic capacity of the water-space will constantly vary. Deductions drawn by comparing surveys taken within limited periods will therefore be unreliable. The effect of the training walls and the removal of the enormous amount of material scoured out of the river as the channel deepened, and

the deepening of the outer channel, would naturally lead to a variation in the contour of the estuary; this would not create additional material, but be merely a transposition, and sand which formerly oscillated backwards and forwards with the tides and floods has now become fixed, with advantage to the permanence of the channels.

The fact as to whether a decrease of the cubic capacity of the water-space has occurred or not, is not so material as the general effect which the training works and enclosure of land have produced on the estuary, which may be briefly stated as follows. The channel, from the end of the training walls to the sea, is now in a better condition for navigation than it was previously, being more stable than it used to be; the channel seaward of Havre has deepened; the time of high water is advanced at Havre; a large body of material that formerly was always being shifted about and forming shoals is now permanently at rest; a valuable tract of land has been brought into cultivation where formerly was nothing but barren sand; and the river above the estuary is now navigable for large ocean-going steamers for a distance of 50 miles inland.

Various schemes for the extension of the training walls, with a view to improving the navigation through the estuary, have been suggested, the main contention arising from the difficulty in laying them out without injuring the ports of Havre on the one side, and Honfleur on the other. A Commission of engineers appointed by the French Government has advised the opening out of the present walls at their mouth, and their extension, so as to give a direction to the main channel along the line of its greatest permanence—that is, between the Amford and Ratier banks, but nearer the latter. To meet the difficulty as to Havre, and to improve its approach, it is proposed that a new entrance in deep water should be constructed more to the west than the present approach, where the low water can be relied on to continue permanently deeper.

It is also proposed that an alteration in the existing channel between Tancarville and Berville should be made by constructing new training walls in a more northerly direction and wider apart; the trained channel to be widened from 1640 to 2950 feet near La Roque, and, where the channel changes its curvature about halfway to Berville, the width to be reduced to 2790 feet, then to widen out again gradually to 4430 feet a little past

Berville; at the next change of curvature, opposite Fatonville the channel to be reduced to a width of 4265 feet, and thence to widen out rapidly to 9840 feet at the end of the training off Honfleur, the outer portion of the walls from Ficquefleur to Honfleur to be kept low, and be gradually raised above this. It is considered that by contracting the channel at the point of reverse curvature a fixed deep channel will be maintained along the banks, and a permanent entrance channel be secured to Honfleur by leading the deep water in front of the jetties. The cost of the estuary work, including the removal of shoals at Quillebeuf, but exclusive of the special works at Havre, is estimated at £1,000,000, the total outlay being put at £4,560,000.

Another plan, which appears to meet with some support, is a modification of that originally proposed by M. Partiot, by which it is intended to suppress two out of the three channels now existing, and concentrate the strength of the flood and ebb in one channel directed towards Havre. To effect this it is proposed to construct a concave training wall about 12 miles in length, extending from the end of the present south training near Berville and running close past Honfleur to the hard shoal of Amford, and thence returning in a southerly direction to the coast at Villerville. By this means the whole force of the flood and ebb would be thrown into the northern channel, which would pass close by Honfleur and be directed towards Havre. It is also proposed to open out the present mouth of the trained channel by removing about 3 miles of the lower end of the north wall and removing it back, so as to make the entrance bell-mouthed. The great objection to this plan is the contraction of the mouth of the bay by the wall running out from Villerville, by which the width of the estuary will be reduced two-thirds, and also the check given to the southern branch of the tide which comes through Villerville Deeps. The combined influence of the two tidal currents is now felt for some distance above Rouen, or for more than 77 miles. It is feared that such a large contraction of the waterway by which the estuary is now fed might seriously interfere with the propagation of the tidal wave up the river. On this ground this scheme is opposed by the French Government engineers.

"Etude sur la Navigation des Rivières a Marées," M. Bouncieau (Paris: 1845); "Monographie du Régime de la Seine

Maritime," M. Belleville (Paris: 1869); "La Seine Maritime et son Estuaire," par E. Lavoinne (1885); "The River Seine," L. F. Vernon-Harcourt, *Min. Proc. Inst. C.E.*, vol. lxxxiv., 1886; "The Tidal Seine," Mengin-Lecreulx (Paris Congress, 1892); Report on the Shipping and Harbour Improvements at Rouen, H. E. O'Neill (Foreign Office Reports, 1892).

The Maas.—This river, called "The Meuse" where it passes through Belgium, and "The Maas" in Holland, gives access to the port of Rotterdam from the North Sea. The works carried out for the improvement of the waterway between Rotterdam and the sea afford an instructive example of the beneficial result of training at the mouth of a river on a low sandy coast, having only a small rise and fall of the tide. The rise of a spring tide is 5 feet 6 inches at the mouth of the jetties, and 4 feet 3 inches at Rotterdam, 21 miles higher up. The fresh-water discharge is very considerable, the volume being larger than most of the great rivers of Europe flowing into tidal seas.

The river Rhine discharges its water into the North Sea through a great number of branches, the most northerly of which, the Maas, passes Rotterdam. The outlet of this branch was originally by a channel passing Brielle. This channel became so silted up at the beginning of the present century that vessels drawing more than 10 feet could not navigate the channel, and the only access to Rotterdam was by the Goereesche Gat, past Hellevoetsluis and round by Dordrecht. About the year 1829 the Hoorne Canal, about 6 miles in length, was cut from Hellevoetsluis so as to avoid the shoals and sandbanks at the mouth of the Maas outfall. This, however, only provided a navigation for vessels drawing 17 feet, and the course was circuitous, occupying 18 hours. Under these circumstances the extension of commerce at Rotterdam was impossible, and it was no longer able to compete with the other ports of Western Europe.

In 1857 the Dutch Government nominated a Commission of engineers of the Waterstaat to report as to the best way of securing an efficient navigable channel from the sea to Rotterdam. In the following year Mr. P. Caland, an engineer of the Waterstaat, presented a scheme for improvement, which was accepted by the Commission, and recommended to the Government for execution. By this scheme it was proposed to adopt

the north arm of the Maas, called the Scheur (see Fig. 74), and to join this to the sea by a new cut about three miles long across the Hook of Holland, and to continue the cut by jetties extending beyond the coast-line until a depth of $16\frac{1}{2}$ feet at low water was reached. At the same time the channel from Rotterdam

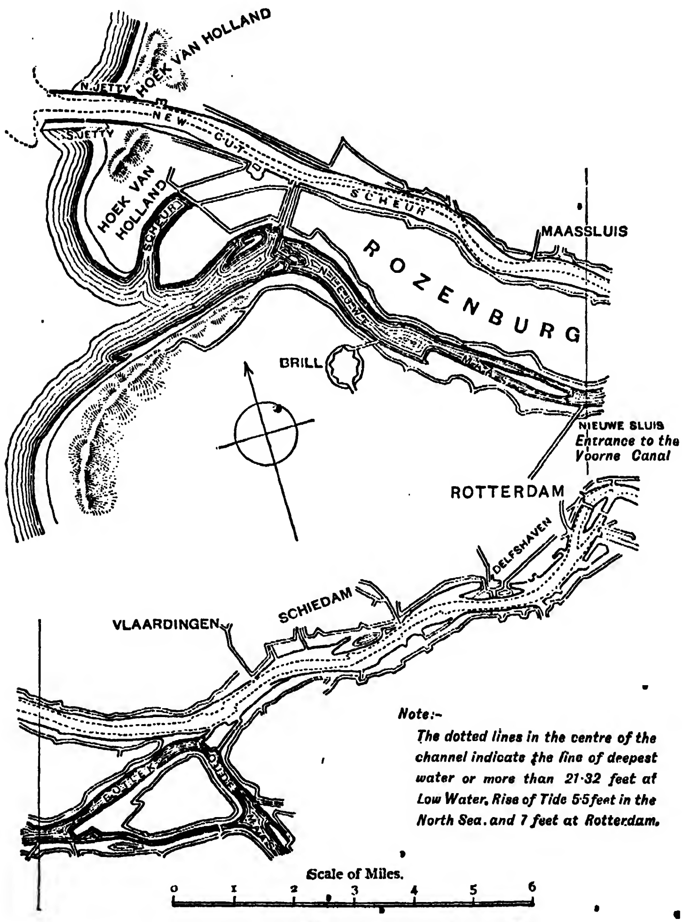


FIG. 74.—River Maas. Rotterdam to North Sea.

was to be deepened and regulated so as to give a width at Rotterdam of 1082 feet, increasing progressively to 2952 feet at the entry between the jetties. The soundings beyond the outer end of the jetties indicated that a depth of $21\frac{1}{2}$ feet could be relied on for the new outfall. The cost of the work was

estimated at £525,000 (fl. 6,300,000), and the time required to complete the work six years. The reason for recommending the cut across the Hook of Holland in place of opening out the old outfall was the absence of sandbanks at the place selected; that the low-water line of 26 to 30 feet approaches very close in shore; and the tide runs stronger there.

The works were commenced in 1863 by the construction of the north, and in the following year of the south pier. In 1868 the cutting of the channel across the Hook of Holland was proceeded with (Fig. 74) to a width of 194 feet, and a depth of 10 feet at low water. The new channel was partly excavated by manual labour, leaving the remainder of the soil to be scoured out by the action of the water. The mouth of the old Scheur was closed to the level of high tide in 1872, and the training of the rivers above the jetties was proceeded with as rapidly as possible, so as to drive all the water into the new cut.

In 1874 the north pier had reached its intended length of 6560 feet, and, two years after, the south pier a length of 7544 feet. These jetties were made of fascine-work, a description of which and illustration are given in Chapter IX. on "Training." The new channel was first opened in 1871 for the use of small vessels, and in 1872 for steamers.

When the piers and training walls were completed in accordance with the original scheme, it was found that the depth did not increase as rapidly as was anticipated. The currents, in widening and deepening the new cut, removed enormous quantities of sand, which became deposited in the wide space between and in front of the piers, and prevented all further deepening and improvement. A Government Commission was appointed in 1877, to inquire into the matter. This Commission finally reported in 1880, advising that the currents should no longer be relied on for widening and deepening, but that this should be assisted by dredging; that the channel should be brought to a uniform width throughout, being made 984 feet at Rotterdam, and 2296 feet at the sea end of the piers; and that, to accomplish this, the banks should be set back where necessary, and the waterway enlarged where the river was too narrow; to raise the piers and extend them into a depth of 29½ feet, and to separate the rivers to the south of Rosenburg from the navigable channel, a lock being constructed at Vlaardingen

to give access from the Oude Maas, and the Bollek. In 1881 the narrowing of the outfall was effected by a low training wall on the south side between the two piers, and a connecting embankment between this pier and the head of the low embankment. The dredging at the mouth of and between the piers was rapidly proceeded with, and the widening near Maasluis began in 1886, involving the setting back of the embankments. These works have proved very successful. The minimum depth in the channel between and beyond the piers increased continually. It reached at low water to 9·84 feet in 1882; 12·13 feet in 1884; 13·12 feet in 1885; 17·38 feet in 1888; 20 feet in 1889; 22 feet in 1890; and 23·61 feet in 1891, giving 29 feet at high water, which is also the minimum depth outside the jetties. These depths are taken over a width of 984 feet.

The 5½-fathom line at low water along the coast has remained unaltered since the commencement of the works. The 4½-fathom line advanced seaward when the jetties were commenced, and continued for a short time, but since 1876 no further advance of this line has occurred. The channel has also continually deepened up to Rotterdam, the minimum depth over a width of 984 feet being 21·32 feet at low water.

The maximum draught of vessels has increased from 19 feet 4 inches in 1882 to 25 feet in 1889. The number of vessels of a draught of 18 feet and upwards has increased from 65 in 1882 to 107 in 1889. The time now taken to get from the sea to the quays at Rotterdam, 20 miles, is two hours.

The quantity of excavation and dredging to the end of 1889 between Rotterdam and the sea amounted to 50½ millions of cubic yards, of which 37½ millions was done after 1881.

The total cost of the work since 1863 up to the end of 1891 has been £2,840,000. It is estimated that a further sum of £200,000 will be required during the next two years to complete the works.

"Les Voies de Navigation dans la Royaume des Pays-Bas" (The Hague: 1890); "Report on the Improvement of the Fluvial Way from Rotterdam to the Sea," M. Welker, Chief Engineer of the Waterstaat at Zwolle (1892); "Report on the Improvement of Navigation from Rotterdam to the Sea," made for the United States Government by Major Barnard (Washington, 1872).

The Danube.—Although the Danube is not a tidal river, it yet affords one of the best examples of river-engineering of which

there is any record. The physical characteristics and natural governing factors of the river were carefully watched and turned to the best advantage. The works were carried out tentatively, and the channel gradually regulated and led into the direction best calculated to obtain the greatest effect from natural scour. The outfall was trained and extended sufficiently far to turn the transporting power of the water to the most effective account, and to a point where the littoral currents were powerful enough to carry away the detritus brought down in floods. The result has been that one of the finest rivers of Europe, the navigable resources of which were confined to the passage of barges owing to the condition of the last fifty miles of its course, is now navigable by steamers of large tonnage, conferring an inestimable advantage on the trade of a very large tract of country. This has been accomplished at a cost which, compared with other works of river-improvement in this or other countries, and with the results obtained, must be considered as exceedingly moderate, and which reflects credit on the skill of the engineering staff employed.

The river Danube has a drainage area of 316,000 square miles. It is 1750 miles in length, and has 300 tributaries. It has a navigable waterway of 1620 miles, or within 130 miles of its source. The discharge in summer floods, when the water attains the level of the natural banks of the delta, at 14 miles below Isaktcha, has been calculated at 325,000 cubic feet per second, of which 205,000 went by the Kilia branch. The Sulina branch (see Fig. 75) discharges $\frac{2}{7}$ of the entire volume, which is about 24,000 cubic feet a second at ordinary high water, when the river is 9 feet above the level at St. George's Chatal. At low water, or when one foot above the sea, the discharge is reduced to 5300 cubic feet a second, the maximum discharge in high floods being 70,600 cubic feet.

The inclination in the surface over the 50 miles of the Sulina branch averages at low water $\frac{1}{4}$ inch in a mile. At high floods it increases to 3 inches in a mile. The velocity varies from 3 to 5·20 miles an hour at the mouth in floods, falling at low water to half a mile.

The weight of sediment carried by the Sulina branch varies from 12 grains to a maximum of 840 grains per cubic foot, the mean annual discharge of solid matter being 5 million tons. The mean annual discharge of the whole river is $67\frac{3}{4}$ million tons, the maximum discharge being 154 million tons.

At a point about 45 nautical miles from the Black Sea, and 15 miles below the town of Isaktcha, the Danube divides into two streams, and the delta commences at the point of divergence. These two main channels again divide into three navigable channels and a number of smaller outlets. At the head of the

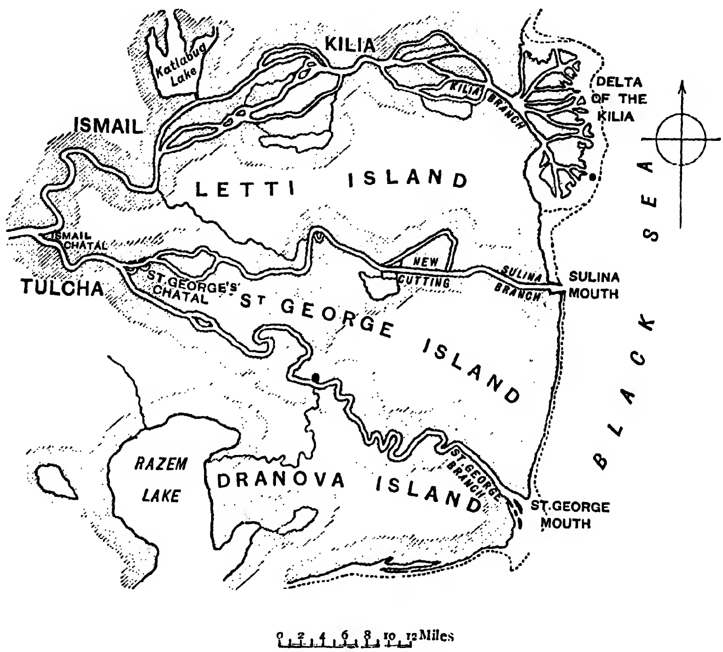


FIG. 75.—Delta of the Danube.

delta the channel is 1700 feet wide, and 50 feet deep. The deepest navigable channel across the bar at the lowest end of the delta was formerly from 7 to 10 feet.

In 1856 a European Commission was appointed for the purpose of determining on the best means of improving the outfall of the river, and for raising the means for carrying out the work. Their jurisdiction extended from Isaktcha to the Black Sea. By the treaty of Berlin in 1878 this was extended to Galatz. Sir Charles Hartley was appointed engineer to the Commission, and under his advice the Sulina branch, the smallest outfall of the three, was selected for improvement.

The Sulina mouth is the most northerly outlet. It was very

winding, and varied in width from 300 to 800 feet. It was impeded by numerous shoals, and was difficult for navigation till within 22 miles of the sea. The entrance to it from the sea was a wild open seaboard strewn with wrecks, the hulls and masts of which, sticking out of the submerged sandbanks, gave to mariners the only guide as to where the deepest channel was to be found. The depth of the channel over the bar varied from 7 to 10 feet, and was rarely more than 9 feet.

In 1857, Sir Charles Hartley advised that the channel should be trained across the bar by provisional works consisting of piles and planking, backed up by rubble stone obtained from the forests and quarries in the neighbourhood. This plan was condemned by an International Commission of engineers, who reported that they could not recommend the application of the proposed system of improvement, as it offered no guarantee of success. The projects for the Sulina mouth they considered would be of no real use; that the guiding piers would soon be destroyed by the force of the waves; that they would cause the loss of large sums of money, and throw obstacles in the way of existing navigation. As a substitute, the technical International Commission recommended the construction of a lateral canal, 16 feet deep, to the St. George's branch from the sea, at a cost of £360,000. The ultimate cost of this canal with maintenance, it was estimated, would have amounted to £600,000. The provisional plan of Sir Charles Hartley, so unsparingly condemned by the Commission but finally carried out and completed in 1861, gave a depth of 17 feet, at a cost of £86,000, and effected a saving to the navigation which has averaged nearly a million a year since it has been carried out.

The training works into the Black Sea consisted of a northern pier extending 3200 feet from the land, and a southern pier 2550 feet. The main piles supported a planking 4 feet above the sea-level, and rubble stone was filled in at the back of the line of piles and allowed to take its own slope up to the water-line. These piers were so constructed as to direct the ebb current in a direct line into the sea, normal to the set of the littoral flow, and were carried out sufficiently far to derive advantage from the littoral current in transporting the solid matter brought down; the distance between them is 600 feet.

On the completion of the piers in 1861, the depth over the bar increased to 17 feet, over a width of 580 feet, entirely by

scour, and Sulina, instead of being the worst harbour, at once became the best commercial port in the Black Sea.

Two years after the completion of the provisional piers, owing to a diminution of the velocity of the ebb current, a bank began to grow up between the pier-heads, and the water shoaled to $13\frac{1}{2}$ feet. An extra length of 650 feet had been given to the north or windward pier, in order to leave a wider opening and to afford shelter for vessels entering. But the projection of a sand-bank immediately off the south pier-head became so considerable that the entrance was only very slightly protected by the north pier during the prevailing north-north-east winds, and this sand-bank was as much in the way as a solid pier would have been, Sir Charles Hartley therefore advised the extension of the south pier 500 feet, in order that, the overlap of the north pier being reduced to 150 feet, the river deposits, during the time when the ebb currents were feeble, might be thrown well clear of the pier-heads instead of between them. The depth over the bar continued to vary for the next five years between 18 and 14 feet. In 1869, owing to the absence of river floods and a velocity of only one mile an hour, the channel fell off to 15 feet over a width of 150 feet, and it was in consequence at last determined, in 1869, to further extend the south pier. Following this extension the depth increased to 22 feet, and an effective navigable depth of 20 feet was secured. In 1873 the sand again made itself manifest at the end of the south pier, the 3-fathom line projecting 200 feet into the jetty channel under the lee of the overlap of the north pier. It was subsequently scoured away, but again reappeared. To prevent the recurrence of this shoaling the south pier was again extended in 1876, so as to bring its extremity opposite the north pier-head. The full current is now maintained to the ends of the piers.

Some very heavy floods which subsequently occurred deepened the channel between the piers where the soil was favourable to erosion, 10 feet, and in one place near the south pier a hole 30 feet deep was scoured out. This undue deepening near the south pier led to the formation of a bank outside the pier-heads, and a shoaling for a short time to $19\frac{1}{2}$ feet. To prevent a further recurrence of this, in 1879 a sill was formed across the pier-heads of rubble stone and ballast from the ships over a width of 100 feet, and having a depth of 25 feet. This produced a regular channel by distributing the discharge between the pier-heads,

and the normal depth of 20½ feet has since been maintained. In 1866 it was determined to convert the provisional piers into solid structures, and this work was completed in 1871.

During the five years which succeeded the completion of the first piers the waves persistently broke down the ridge of stonework to the level of from 3 to 4 feet below the water-line; at this depth, except at the pier-heads, the top of the rock remained intact. The mound assumed a slope of 2½ to 1 on the sea side, and 1½ to 1 on the inside. On this base a concrete wall was built 10 feet high and 10 feet wide. The proportion of cement used to gravel and sand was as 1 to 3 for the lower part of the walls, and as 1 to 6 for the upper part. The outer part of the walls, where more exposed to the violence of the sea, was made of blocks weighing 18 tons, composed of 1 of cement to 7 of gravel and sand, immersed when ten days old.

The total length of the north pier is 5332 feet, and of the south pier 3457 feet. The total sum expended on these piers was £185,352, including the sum expended on the provisional piers, making the cost £21 per lineal foot in an average depth of 14 feet of water. Taking the consolidated part only, 6334 feet in length, the cost was £26 per foot in an average depth of 16 feet, including the provisional works. The original estimates for the work presented to the Commission by the engineers called in to report varied from £307,200 to £384,000.

The circumstances which led to the carrying out of the tentative works and their subsequent consolidation were the means of improving the navigation to a depth 4 feet greater than was anticipated, at about half the estimated cost. The construction also in the first instance with great rapidity of simple training works of timber and stone, such as the nearest forests and quarries produced, and then consolidating them later on with concrete when the stone had been beaten down to its ultimate level by the action of the waves, proved the most economical and effective course that could have been pursued.

Since the consolidation of the piers there has not been any advance of the delta at the Sulina mouth. The advance of the 4 and 5 fathoms line of soundings averaged 94 feet a year previous to the commencement of the works. Between 1861 and 1871 it only amounted to 44 feet, the littoral current being strong enough at the point to which the piers were carried to carry away the detritus brought down.

The increase in depth from 9 feet in 1857 to 20 feet in 1872 had the following effect on the navigation of the port: In 1853, 2490 vessels of 339,457 tons left the port; in 1869, 2881 vessels of 676,960 tons cleared seawards. The average tonnage on the former occasion was a little over 132 tons; on the latter, nearly 266 tons. The number of wrecks had decreased from an average of about 1 in 250 to 1 in 5000. In 1890 the number of vessels had decreased to 1519, but the average tonnage had increased to 754 tons, many of the steamers being from 1400 to 1600 tons.

Before the works were completed, it was necessary for ships to convey the cargoes to and from the ships in barges, at a cost of 2*s.* 6*d.* a ton. This is no longer necessary. The dues imposed for ships over 300 tons towards defraying the costs incurred by the Commission were 2*s.* 3*d.* when loading at Sulina, and 3*s.* when loading up the river. Owing to the increase in tonnage, these have since been reduced to 1*s.* and 1*s.* 6*d.* for ships of over 1000 tons, these being the maximum rates. For smaller vessels the rates are less.

The depth of the channel over the greater part of the Sulina branch, from the piers to its junction with the main river at St. George's Chatal, was not more than from 7 to 8 feet. It was impeded by large shoals deposited during heavy floods, especially in those parts of the channel which were abnormally wide; and also in the long straight reaches, where, instead of following along one bank, as in the curves, the current meandered over the whole area of the river-bed from bank to bank. Shoals were also frequently formed at the points where one curve changed into another. These shoals, formed in floods, diminished in the low-water season.

The navigation was also impeded by the numerous bends in the channel, no less than eleven existing in the course of 52 miles, their radius varying from 800 to 1000 feet. Those having a radius of 1600 feet were not found to interfere with the navigation.

In 1870 a cut was made between the twenty-third and twenty-fourth mile, which shortened the course upwards of a mile, and did away with three of the sharpest bends. The length of this cutting was 1900 feet; its bottom width 180 feet, and depth 16 feet below sea-level. This cutting was widened in 1875 to a bottom width of 260 feet, and at the water-line of 300 feet.

At the upper end of the Sulina channel, a shoal in the Tulcha branch near Ismail Chatal was permanently removed by a curved dyke of rubble stone 1400 feet in length, connected to the shore at the Chatal by a straight groyne 600 feet long.

The width of the upper part of the branch varied from 500 to 800 feet, and that of the lower half from 600 to 750 feet. Shoals existed wherever the width exceeded 500 feet, and it was therefore determined to limit the river to the width that Nature indicated as most likely to give a depth of 15 feet. Experience also showed that dredging alone was inadequate to ensure permanent improvement, as, owing to the vast amount of detritus carried in suspension, as well as to the sand rolled along the bottom, the velocity in the wide part was not sufficient to remove this from the river. The channel was therefore contracted in the widest places by groynes to 400 feet in the upper part and 500 in the lower part, followed up by longitudinal walls.

Two hundred and fifty groynes were constructed, many of which are now entirely incorporated with the land accreted where they were placed. The groynes were built at right angles to the river-bank on the convex side. In places where the current had a tendency to impinge, the distance between them was the same as the width of the river after its contraction. In straight reaches the distance was double the width of the channel. These groynes were constructed in the following manner: Piles were first driven 20 feet apart, the tops being level with the river-bank, and the head pile 2 to 3 feet higher, to indicate the centre line and the position of the groyne in high floods. They were built to 4 feet above sea-level, with slopes of 1 to 1, and top width 4 feet. The material used was reed or willow fascines mixed with clay dredged out of the river, bound together with iron wire, and protected with rubble stone.

In 1882 a new cut was made at St. George's Chatal to improve the entrance from the Tulcha branch, which was constantly shoaling in floods. This cut was 3300 feet long, 24 deep, giving 16 feet at low water, and was made to a bottom width of 300 feet, with slopes $1\frac{1}{2}$ to 1 and 1 to 1, and involved the excavation of over a million cubic yards of clay and sand, which was removed by dredgers, floating tubes, and hopper

barges. It did away with two sharp bends, and shortened the course 2900 feet.

Nine of the worst shoals have been successfully dealt with; three cut-offs have been made, by which the river has been shortened 2 miles; eight of the worst bends have been entirely suppressed; and a length of stone revetment to protect the banks has been constructed.

Upwards of 21 miles of revetments have been constructed to prevent undue scour produced by the narrowing of the river. These revetments consist of a layer of rubble stone carried from the bottom of the river-bank to the water-line, where a berm 6 feet in width was formed, the bank above being cut to a regular slope varying from 1½ to 1 to 2 to 1. The slope is covered with roughly levelled rubble having a thickness of 1 to 2 feet. In soft sandy places willow fascines have been used for protection.

The permanent shoals of hard material were removed by dredging, and free material was also removed at times to give temporary relief to the navigation. The total quantity dredged up to 1890 was over 5 million cubic yards, which was removed by 1 bucket ladder dredger, 10 hopper barges of 100 tons capacity, 2 tugs, and 1 suction dredger; the cost of dredging, including transport 2 miles, was 4·011*d.* with the bucket dredger, and 2·402*d.* with the suction dredger. The allowance to cover cost of plant was estimated at 1·098*d.* per cubic yard.

By the training works the channel is now so regulated that shoaling rarely occurs even after floods, and a steady depth of 17 feet throughout is maintained.

The total cost of the works on the Sulina branch, including the training and new cuts, up to the end of 1890 was £424,242.

Between the eighth and eighteenth mile from the piers the river makes a great detour, in which are sharp bends with a radius of from 1000 to 1200 feet. These are found to give trouble to long steamers, and hinder the progress of the drifting ice. In June, 1890, a new straight cut between these points was commenced, which will shorten the distance 4¼ miles. The length of the cut is 5¼ miles, and 6½ million cubic yards of material will have to be dredged. It is expected that the cut will be completed in 1895.

"The Danube," by Sir Charles Hartley, in Lectures on Hydro-Mechanics, *Inst. C.E.*, 1885. "The Delta of the Danube," 1862, and "Recent Changes along the Sea Coast of the Delta of the Danube," 1873, both by Mr. C. A. Hartley, *Min. Proc. Inst. C.E.*, vols. xxi. and xxxvi.; "Dredging the Lower Danube," by L. C. H. Kuhl, vol. lxv., 1881; "The Sulina Mouth of the Danube," by Kuhl, vol. xci., 1888; and vol. cvi., 1891.

APPENDIX I.

Titles of Books relating to Tidal Rivers.

A General History of Inland Navigation, Foreign and Domestic, by J. Phillips. London: 1803.

Historical Account of the Navigable Rivers and Canals of Great Britain, by Joseph Priestley. London: 1831.

A System of Mechanical Philosophy, by J. Robison. Articles on the Theory of Rivers, and on Tides. Edinburgh: 1822.

Report of the Tidal Harbour Commissioners. First Report, 1845; Second Report, 1847, with Minutes of Evidence and Appendix. London.

Return made to the House of Commons in 1883, giving description of works executed within the last twenty years at the various ports in the Kingdom.

Treatise on the Improvement of the Navigation of Rivers, by W. A. Brookes. London: 1841.

The Conservation and Improvement of Tidal Rivers, by E. K. Calver. London: 1853.

Principles and Practice of River Engineering, by D. Stevenson. Second Edition. Edinburgh: 1872.

The Design and Construction of Harbours, by T. Stevenson. Edinburgh: 1874.

A Treatise on Rivers and Canals, by L. F. Vernon-Harcourt. London: 1882.

Harbours and Docks, by L. F. Vernon-Harcourt. London: 1885.

River Bars, by J. T. Mann. London: 1881.

Manual of Hydrology, by N. Beardmore. London: 1862.

Hydraulic Tables and Coefficients. Third Edition. J. Neville. London: 1875.

Elements of Practical Hydraulics, by S. Downing. London: 1875.

Practical Hydraulics: Tables, etc. T. Box. London: 1876.

Simple Hydraulic Formulæ. T. W. Stone. London: 1881.

Kutter's Hydraulic Tables, translated by L. D'A. Jackson. London: 1876.

Hydraulic Manual, by Lewis D'A. Jackson. Fourth Edition. London: 1883.

A Treatise on Hydraulics, by M. Merriman. New York: 1890.

Irrigation Canals and other Irrigation Works, including the Flow of Water in Irrigation Canals and Open Channels, with Tables simplifying the application of the formulæ of Kutter, D'Arcy, and Bazin, by P. J. Flynn, C.E. San Francisco: 1892.

On the Movement of the Water in a Tidal River, with reference to the Position of Sewer Outfalls, by W. Cawthorne Unwin. London: 1883.

Tides and Waves. Airy. Encyclopædia Metropolitana.

The Tides. Robison's Mechanical Philosophy, vol. iii. 1822.

Report on Waves. J. Scott-Russell. British Association: 1842–3.

Manual of Tides and Tidal Currents. S. Haughton. London: 1857.

A Manual for Tidal Observation. A. W. Baird. 1886.

The Tides. W. Parkes. London (out of print).

An Elementary Treatise on the Tides. J. Pearson. London: 1881.

Time and Tide. R. S. Ball. London: 1889.

Tide Tables for the British and Irish Ports. Hydrographic Department, Admiralty, annually. London: Potter.

Annuaire des Marées des Côtes de France. Service Hydrographique. Annually. Paris.

The Channel Pilot, North Sea Pilot, and Sailing Directions for all Parts of the World. Hydrographic Department, Admiralty. London: Potter.

General Instructions for Hydrographical Surveyors. Admiralty. 1888.

Hydrographic Surveying. W. J. L. Wharton. London: 1882.

The Mississippi and Ohio Rivers, by C. Ellet. Philadelphia: 1857.

Report upon the Physics and Hydraulics of the Mississippi River, by A. A. Humphreys and H. L. Abbott. Philadelphia: 1861.

Hydraulics of Great Rivers; the Parana, the Uruguay, and the La Plata Estuary, by J. J. Revy. London: 1874.

History of the Jetties at the Mouth of the Mississippi River, by E. L. Corthell. New York: 1881.

Industrial Rivers of the United Kingdom. London: 1888.

The River Tyne, by James Guthrie. London: 1880.

The Clyde, from its Source to the Sea, by W. J. Millar. 1888.

Our Sea Marks: an account of Lighthouses, Beacons, Buoys, etc. E. Price Edwards. London: 1884.

A Treatise on Rivers and Torrents, by Paul Frisi. 1762. Translated by Major-General Garstin. London: 1861.

Handbuch de Mechanick and des Hydraulick, by Eytelwein. English translation by Nicholson.

The Measurement of Running Water, by Castelli. Translated by T. Salusbury. London: 1661.

Della Natura de Fiumi, by Guglielmini. 1697.

Traité d'Hydraulique a l'usage des Ingenieurs, by J. T. D'Aubuisson de Voisins. Paris: 1834.

Étude de la Navigation des Rivières a Marées, par M. Bouncieau, Paris: 1845.

Memoir diverse questions interessant les fleuves a Marée, par M. Mengin. Rouen: 1890.

Memoir sur la Puissance Hydraulic des fleuves a Marée, par M. Mengin. Paris: 1889.

Étude sur le Mouvement des Marées, dans la partie Maritime des fleuves, par M. M. L. Partiot. Paris: 1861.

Étude sur les Rivières a Marée et sur les Estuaires, par H. L. Partiot. Paris: 1892.

Monographie du Régime Hydraulique de la Seine Maritime, par M. Belleville. Paris: 1889.

Report on the Tidal Seine, by M. Mengin-Lecreulx. Paris: 1892.

APPENDIX II.

Equivalent English Words for French Hydraulic and Nautical Terms.

Amont, the upper part of a river. *En amont*, up a river.
Amplitude, height (of the tide).
Argile, clay; Dutch, *klei*.
Anse, an inlet, or small bay.
Aval, the lower part. *En aval*, down a river.

Babord, port or left side.
Balise, a beacon or buoy.
Barrage, a weir or dam.
Barre, bar at the mouth of an estuary.
Bas fond, a shoal.
Bassin, wet dock.
Boie, a creek.
Bord, the shore.
Bouche de rivière, mouth of the river.
Boue, mud,
Bouée, buoy.
—— *de sauvetage*, life-buoy.
Boueux, oozy or muddy.
Bouffée de vent, gust of wind.
Brasse, a fathom; Dutch, *vaden*.
Brisants, breakers or surf; Dutch, *breekers*.
Brouillard, fog.

Cailloux, pebbles.
Chenal, channel; Dutch, *kanaal.*
Chute, fall. *Chute d'eau*, waterfall.
Côte, coast, seashore.
Cote, figure, number.
Coté, side, beam end.
—— *sans le vent*, lee side.
—— *du large*, offing.

Courant, current or stream.
Crue, flood, freshet.

Débarcadère, landing-place.
Débit, discharge, quantity of water a channel will convey.
Déblais, excavation.
Dépôt, deposit (of alluvial matter or sand).
Dérive, drift or leeway.
Dérocher, to break up rock.
Digues, embankment, dyke, or training wall; Dutch, *dijk*.
Draggage, dredging.
Drague, dredger.
Douce eau, fresh water.

Eau, water.
—— *de mer*, salt water.
——, *douce* or *fraiche*, fresh water.
Eau grande, high flood.
—— *morte*, neap tide.
—— *vive*, spring tide.
Échelle, scale.
—— *hydrométrique*, gauge.
Écluse, lock of a canal.
Écoulement, efflux.
Écueil, shoal.
Est, east.
Étale, slack of the tide.
Étiage, low-water mark, low water in a river as compared to the height in freshets.
Évitée, berth for a vessel, swinging-room.
Éviter, to swing a vessel.
—— *a la marée*, to stem the tide.

Falaise, cliff.
Fanal, a beacon light.
——, *fixée*, fixed light.
—— *de port*, harbour light.
——, *flotant*, light-vessel.
——, *tournant*, revolving light.
Fascine, a faggot, training work in a river formed with faggots.
Flot, flood-tide. *Demi-flot*, half-tide, wave, surge.
Fond, bottom. *Bas fond*, a shoal. *Haut fond*, a shoal.
Frottement, friction.

Galet, shingle.
Gouflement, swelling (of the tide).
Gravier, gravel.
Griffe, grab (of dredger).

Haut fond, shoal.
Havre, harbour, port.

Jusant, ebb tide.

Large, or *côte du large*, offing.
Largeur, width.
Ligne de sonde, sounding-line, lead-line.
Lit, bed of (a river or the sea).
Loch, log.
——, *livre de*, log-book.
——, *jeter le*, to heave the log.

Maigres, shoals.
Marée, tide.
——, *haute*, high tide.
——, *basse*, low tide.
——, *arrétante*, slack of tide.
——, *montante*, rising tide.
——, *descendante*, falling tide.
Marque de mer, sea-mark.
Mer, the sea.
——, *coup de*, a billow.
——, *gros coup de*, heavy sea.
Mouillage, anchorage, navigable depth of water.
Mouille, deep water.
Marais, marsh.
Mascaret, bore or tidal wave.

Nœud, knot.
Naufrage, wreck.
Niveau, level (of high or low water).
—— *de l'eau*, water-line.
—— *des eaux*, water-mark.
—— *de basse*, low-water line.
—— *moyen de la mer*, mean level of the sea.
Nord, the north.

Orage, storm.

Onde, wave.
Oueste, west.

Pente, slope of the surface.
Phare, lighthouse.
——, *flamboyant*, flashing light.
Pied, a foot.
Pilot, pile, pilotage, pile-work.
Pilote, pilot.
—— *bateau*, pilot-boat.
Planche, plate of illustrations.
Port, port, wharf, quay.
—— *de mer*, seaport.
——, *surgir a*, to land.
Pouce, an inch.
Profondeur, depth.

Rade, roadstead.
Remorqueur, tug-boat, boat used for traction by chain or wire in canals.
Rivage, beach.
—— *sous le vent*, lee shore.
Rive, bank of a river.
Rivière, river.

Sable, sand.
——, *mobile*, shifting, or quicksand.
——, *vaseaux*, sand mixed with mud silt.
Sablou, fine sand.
Salure, saltness, salt water.
Seau, bucket of a dredger.
Seuil, sill of a lock, hard shoal or bar.
Sifflet de brouillard, fog-whistle.
Sondage, sounding.
Sonde, ligne de, sounding-line.
Sonder, to sound.
Sous le vent, lee side.
Sud, south.

Terre firme, mainland.
Thalweg, the line of deepest water in a channel, the navigable channel in a river.
Tirant, draught of a vessel.

Tonée, hauling-line or rope, a warp.
Tonnage, tonnage.
Tonne, can-buoy.
Treuil, a winch.

Vague, wave,
——, *grande*, high wave.
Vase, silt.
Vent, wind.
—— *alizé*, trade wind.
—— *sous le vent*, to leeward.
—— *au vent*, to windward.

APPENDIX III.

English and Foreign Measures.

	English feet.	English statute miles.	Kilometres.	Number of to a degree of latitude.
Nautical mile ..	6076·98	1·1509	1·8516	60·0
Admiralty mile ..	6080·0	1·1515	—	—
Statute mile ..	5280·0	1·0	1·6089	69·06
Irish mile ..	6720·0	1·2728	2·0477	54·26
Scotch mile ..	5952·0	1·1273	1·8137	61·26
Kilometre ..	3281·0	0·6214	1·0	111·20

	Yards.	Statute miles.
League, French, marine	6086	3·46
„ „ land	4861	2·76
„ Portugal	6760	3·95
„ Spain	7416	4·21
„ Holland	6395	3·64

Li, China .. varies from	0·22 to 0·36 English mile
Archine, Russia	2·333 feet
Sagene, „	7 feet
Verst, „	1067 metres = 0·6628 English mile
1 pik, Turkish	26·625 inches
1 „ Egyptian	22 to 27 „
1 palm, Italy	0·732 foot
1 brace or cubit, Florence ..	1·66 „

Nautical Measures.

Fathom	6 feet.
Cable	608 feet = $\frac{1}{10}$ nautical mile
Knot	one nautical mile an hour

1000 fathoms are generally taken as equal to 1 nautical mile.

	English feet.	Reciprocal for English fathoms.
Sashine, Russian	6·0	1·0
Brasse, Old French	5·329	0·881
Metre, recent "	3·281	0·547
Favn, Danish and Norwegian	6·175	1·0292
Famn, Swedish	5·843	0·974
Vaden, Dutch	5·575	0·929
Elle, Dutch, recent	3·281	0·547
Braca, Portuguese	6·004	1·0
Faden, German	5·906	0·984
Metro, Spanish	3·281	0·547

METRICAL MEASURES AND RECIPROCALS.

	Equivalent in England.	Reciprocal.
Millimetre	0·03937 inch	25·399
Centimetre	0·39371 "	2·5399
Decimetre	3·9371 "	0·2540
Metre	3·2809 foot	0·3048
"	1·0936 yard	0·91438
Kilometre	0·6214 mile	1·6093
"	1093·633 yards	—
Nœud	6086 yards	—
Litre (1 cubic decimetre)	1·7607 pint	0·56793
"	0·220 gallon	4·54345
Hectolitre (100 litres)	22·0096 "	0·45434
Gramme	15·43267 grains	0·06479
"	0·035273 oz. avd.	28·3439
Kilogramme	2·20485 lbs. "	0·4536
Tonne	2204·621 lbs.	—
"	0·9842 ton	—
Square metre	10·7643 square feet	0·0929
"	1·1936 square yard	0·83609
Cubic centimetre	0·061 cubic inch	16·386
Cubic metre (stère)	35·3165 cubic feet	0·283
"	1·308 cubic yard	0·7645

Pint of water	0·02005 cubic feet	
"	weighs 1·25 lb.	
Gallon of water	weighs 10 lbs.	
"	measures 277·27384 cubic inches	
"	0·16051 cubic foot	

Gallon of sea-water	.. ..	weighs 10·20 lbs.
Cubic inch of water	.. ..	0·0036 gallon
Cubic foot of water at 60°	..	62·32 lbs.
„ „ generally taken as		62·5 lbs.
„ „	.. ..	0·0279 ton
„ „	.. ..	6·2355 gallons
Cubic yard of water	.. ..	1687·5 lbs.
„		0·756 ton
Ton of water	.. .. ..	35·84 cubic feet
„	.. .. ..	224 gallons
Cubic metre of water	.. ..	0·985 English ton
Minute	.. ..	·0166 hour

	Multiplier.	Reciprocal.
Feet per second into miles per hour	0·682	1·467
Feet per minute „ „	0·01137	88
Metres per second „ „	2·2363	0·447
Metres per minute „ „	0·03727	26·82
Kilometres per hour into feet per second ..	0·9114	1·097
Feet per second into knots per hour	0·592	1·690
Nautical miles per hour into statute miles ..	1·1509	0·8688
Price per cubic metre to price per cubic yard	0·914	1·095
To change grains in 100,000 parts to grains per gallon	0·7	—
To find increased draught of a vessel passing from salt to fresh water, multiply draught by	1·029	0·972

To convert metrical measures into English, multiply by the figures given in the first column of the table of metrical measures; and to convert English into French measures, multiply by the reciprocal numbers in the second column.

APPENDIX IV.

ABBREVIATIONS USED IN THE ENGLISH ADMIRALTY CHARTS.

Anchge., anchorage.
B., bay.
B., black.
B.W.V.S., black and white vertical stripes (near a buoy).
B. W. H. S., ditto horizontal.
Baty., battery.
Bk., bank.
C., cape.
C. G., coast-guard.
Cathl., cathedral.
Ch., church.
Chan., channel.
Cheq., chequered (near a buoy).
Cold., coloured.
Cr., creek.
E. D., existence doubtful.
Flg. Lt., floating light.
Fms., fathoms.
Ft., feet or foot.
G., gulf.
Gt., great.
H., hour.
Hd., head.
Ho., house.
Hr., harbour.
H. S., horizontal stripes (near a buoy).
H. W., high water.
H. W., F., and C., high water, full, and change.
I., island.
Is., Islands.
Kn., knots.
L., lake.
Lat., latitude.
Long., longitude.
Lt., light.
Ditto, horizontal.
Lt. Alt., light alternating.
Lt. F. & Fl., light fixed and flashing.
Lt. F., light fixed.
Lt. Fl., light flashing.
Lt. Int., light intermittent.
Lt. Occ., light occulting.
Lt. Rev., light revolving.
L. W., low water.
M., nautical mile.
Magn., magazine.
Magc., magnetic.
Min., minutes (near a light).
Mt., mountain.
Np., neaps.
Obsn. Spot., observation spot +.
P., port.
P. D., position doubtful.
Pk., peak.
Pt., point.
R., river.
R., red (near a buoy).
Rf., reef.
Rk., rock.
Sd., sound.
Sec., seconds (near a light).

Sh., shoal.
Sp., springs.
Str., strait.
Tel., telegraph.
Varn., variation.
Vil., village.
Vis., visible (near a light).
V. S., vertical stripes (near a buoy).
W., white
W. Pl., watering-place.

Nature of the Bottom.

b., blue.
blk., black.
br., brown.
brk., broken
c., coarse.
cl., clay.
crl., coral.
d., dark.
f., fine.
g., gravel.
gl., globigerina.
gn., green.
grd., ground.
gy., gray.
h., hard.
m., mud.
oys., oysters.
oz., ooze.
peb., pebbles.
pt., pteropod.
r., rock.
rot., rotten.
s., sand.
sft., soft.
sh., shells.
spk., speckled.
st., stones.
stf., stiff.
w., white.
wd., weed.
y., yellow.

All soundings in feet or fathoms below mean low water of ordinary spring tides.

Underlined figures indicate feet above low water.

Velocity of the tide is expressed in knots; the period of the tide being shown thus: 1st Qr.; 2nd Qr.; 3rd Qr.; 4th Qr.: Qr. standing for quarter.

Rise of the tide is measured from mean low water of ordinary spring tides.

Range of the tide measured from the low water of one tide to the high water of the following tide.

All bearings are magnetic.

Bearings of lights are given as seen from seaward.

APPENDIX V.

NOTATION ADOPTED.

V = mean velocity in feet per second.
A = area of the cross-section.
P = perimeter or wetted contour.
R = hydraulic mean depth, or the area divided by the perimeter, $\frac{A}{P}$.
S = sine of the slope, or the length divided by the fall; thus 1 foot per mile = $\frac{1}{5280}$.
D = depth of channel in deepest part.
B = width at surface of water.
Q = discharge in cubic feet per second.
C = a number to be determined by experiment.
F = fall in feet in one mile.

All units of length, time, and weight, unless otherwise expressed, are in English feet, seconds, and pounds.

APPENDIX VI.

Datum Marks and Mean Level of Sea.

The datum used in England is the datum of the Ordnance Survey, or adopted mean sea-level at Liverpool.

The figures are principally obtained from the third report of the Committee of the British Association appointed to consider the tabulation and comparison of datum marks (Report, 1879); the "Compte Rendu Association Française pour l'avancement des sciences," 1890 (L'unification des altitudes et le niveau des mers en Europe); and the Ordnance Survey of England.

The figures in the table refer to a datum taken 100 feet below Ordnance datum.

	Feet.
English Ordnance datum: mean sea-level at Liverpool ..	100·00
Trinity high-water standard: Thames datum	112·50
Irish Ordnance datum (approximately)	92·54
French datum (approximately): zero du Nivellement (Bourdaloue) mean sea-level at Marseilles	100·00
Belgium: zero du depôt de la Guerre	93·50
Holland: Piel d'Amsterdam, A.P.	100·93
Avonmouth: inner sill of lock at channel dock	92·50
Barrow: outer sill Ramsden Dock	82·75
Belfast: harbour datum	95·46
Birkenhead: outer entrance Alfred Dock	83·33
Bristol: sill of Cumberland basin	89·42
Boston: dock sill	88·46
,, Black Sluice sill (drainage datum)	91·30
Clyde: Clyde datum	113·81
Cardiff: sill of sea gates, Bute Dock	89·28
Dublin: North-Wall standard	93·97
Dee: Cheshire, zero tide-gauge Chester (Dee standard is 15 feet above zero of this gauge)	101·38
Dee: Aberdeen, sill Victoria Dock	85·38
Dover: zero of tide-gauge, Admiralty pier	91·30

Mers.	Postes d'observation.	Cotes de Niveau moyen par rapport au niveau moyen actuel de Marseille. d'après les plus récentes opérations. Centimetres.
Mer du Nord	Ostende	− 16
	Flessingen	− 7
	Bromvorshaven	− 8
	Ymuiden	− 5
	Helder	− 4
	Staroven (Zuiderzée)	+ 6
	Elburg (*id.*)	+ 7
	Nykerk (*id.*)	+ 5
	Amsterdam (*id.*)	− 1
	Holingen	+ 1
	Delfzijl	− 1
	Cuxhaven	− 3
Baltique	Travemünde	− 9
	Varnemünde	− 4
	Swinemünde	− 2
	Neufahrwasser	− 1
	Pillau	− 8

Variation at Places on the English Coast in the Mean Level of the Sea from the Datum adopted at Liverpool for the Ordnance Survey.

Mean Level of Sea.

	Above. Feet.
Hull	0·038
Sunderland	0·064
Southampton	0·141
Ramsgate	0·324
Shields	0·340
Lowestoft	0·732
Sheerness	0·798
Lynn Cobb	0·840
Grimsby	1·164
Norwich	1·233
London Bridge	1·790

Mean Level of Sea.

	Below. Feet.
Weymouth	0·089
Pembroke	0·096
Holyhead	0·188
Torquay	0·217
Dover	0·233
Berwick	0·261
Scarboro'	0·316
Portsmouth	0·348
Shoreham	0·461
Weston-super-Mare	0·529
Penzance	0·646
Liverpool (local datum obtained from self-register gauge)	0·650
Falmouth	0·651
Plymouth	1·009
Silloth	1·283

Simplifying this by dividing out g—

$$\frac{h}{l} = \frac{C}{g} \times \frac{P}{A} \times V^2 \qquad (3)$$

And as g is constant, put $\frac{C}{g} = C'$.

Solving, then, for C'—

$$\frac{h}{l} \times \frac{A}{P} \times \frac{1}{V^2} = C' \qquad (4)$$

from experiments it is found that—

$$C' = 0{\cdot}0001, \text{ and } \frac{1}{C'} = 10{,}000$$

Solving for V—

$$V = \sqrt{\frac{h}{l} \times \frac{A}{P} \times 10{,}000}$$

$$\text{or } V = 100\sqrt{\frac{h}{l} \times \frac{A}{P}}$$

$$V = 100\sqrt{SR}$$

Taking for l one mile, and putting F for the fall in that length in feet—

$$V = 100 \times \sqrt{\frac{F}{5280} \times R}$$

$$= \frac{100}{72{\cdot}66} \times \sqrt{FR}$$

$$= 1{\cdot}38\sqrt{FR}$$

and as $1{\cdot}38 = 0{\cdot}92\sqrt{2}$, by substituting this value—

$$V = 0{\cdot}92\sqrt{2FR} \text{ in feet per second}$$

or, for feet per minute, as $0{\cdot}92 \times 60 = 55{\cdot}2$—

$$V' = 55\sqrt{2FR}$$

which is the same as the formula given by Beardmore.

APPENDIX VIII.

TABLE SHOWING AMOUNT OF SOLID MATTER IN SUSPENSION IN RIVERS.

River.	Solid matter in suspension in one cubic foot of water.		Proportion in weight of solid matter to water.	Remarks.
	lbs.	grains.		
Mersey—flood tide ...	—	100·36	$\frac{1}{4330}$	Upper estuary. Dry weather.
ebb tide ...	—	138·47	$\frac{1}{3150}$	Evidence—Manchester Ship Canal.
Humber	0·284	—	$\frac{1}{224}$	Oldham.
Ouse—Goole	—	299·04	$\frac{1}{1438}$	A. F. Fowler.
	0·320	—	$\frac{1}{191}$	
Trent—Torksey	—	166·25	—	Quarter flood (Wheeler).
Stockwith ...	—	261·87	—	Half ebb do.
Trent Falls ...	—	1905	—	Low water do.
" ...	—	3150	—	First of flood do.
Humber—near Albert Dock	—	201·87	—	High water.
Spurn Point ...	—	135	—	Half flood.
Ribble—flood tide ...	—	121·54	—	Near Lytham (Wheeler).
"	—	—	—	Half flood, 10 feet below surface.
"	—	97		Ditto (Abernethy), average of flood and ebb.
Liffey—calm	—	12·46	—	At the bar, 20 feet below surface (Mann).
rough	—	37·38	—	
Thames—Greenwich ...	—	109·02	—	High water (Bazalgette).
London Bridge	—	16·82	—	
Tilbury L. W....	—	135·19	—	
Tilbury Dock—outer basin	12·9	—	$\frac{1}{3}$	4 feet from bottom, dredging machinery at work.
H. W. ...	0·294	—	$\frac{1}{210}$	28 feet from bottom, do.
half ebb ...	2·945	—	$\frac{1}{22}$	18 feet, do.
Dee	1·05	—	$\frac{1}{60}$	Last quarter ebb (Taylor).
Tees—floods	1·947	—	$\frac{1}{33}$	Fowler.
ordinary	—	205·6	$\frac{1}{2121}$	
Boston Deeps	—	50	$\frac{1}{8777}$	At the surface, half ebb (Wheeler).
	—	90	$\frac{1}{4988}$	15 feet below surface (do.).
Witham, in flood	—	100	$\frac{1}{4375}$	8 feet below surface (do.).
Welland—Fosdyke Bridge	—	342·65	$\frac{1}{1273}$	Strong ebb (do.).
Spalding ...	—	710	$\frac{1}{614}$	Deposit being stirred up (Wheeler).
Ordinary flow...	—	87·22	$\frac{1}{5000}$	

River.	Solid matter in suspension in one cubic foot of water.		Proportion in weight of solid matter to water.	Remarks.
	lbs.	grains.		
Glen	—	1120	$\frac{1}{308}$	Strong ebb (Wheeler).
Ouse, near Denver ...	—	181	$\frac{1}{2413}$	From surface, ordinary flow (do.).
Po	0·208	—	$\frac{1}{300}$	Geike's Geology.
Maas, in December ...	—	207·45	$\frac{1}{2100}$	Geike.
Garonne	0·624	—	$\frac{1}{100}$	Geike.
Tiber—mean, 6 years ...	0·0746	—	$\frac{1}{833}$	Shelford.
maximum, 6 years	1·897	—	$\frac{1}{32}$	
Durance—floods, mean ...	1·87	—	$\frac{1}{33}$	
max. ...	6·25	—	$\frac{1}{10}$	
mean	—	795	$\frac{1}{550}$	
Mississippi—mean ...	—	290·3	$\frac{1}{1500}$	Humphreys and Abbott.
max. ...	—	—	$\frac{1}{681}$	
Danube—mean	—	147	$\frac{1}{3060}$	Taken from the surface.
max.	—	940	$\frac{1}{463}$	Mean of ten years.
min.	—	6	$\frac{1}{30030}$	Sir C. Hartley.
Irrawaddy—floods ...	—	256·87	$\frac{1}{1700}$	Login.
ordinary flow	—	76	$\frac{1}{5725}$	
Godavery	—	—	$\frac{1}{1100}$	Of bulk.
Nile—flood...	—	—	$\frac{1}{674}$	Sir C. Hartley.
low water	—	—	$\frac{1}{21000}$	
Ganges—floods	0·146	—	$\frac{1}{428}$	Geike.
mean	—	—	$\frac{1}{510}$	
Indus	0·264	—	$\frac{1}{237}$	
Rhone—floods	0·272	—	$\frac{1}{230}$	At Arles (Geike).
mean	—	—	$\frac{1}{2000}$	
max.	1·39	—	$\frac{1}{45}$	Greatest recorded (Geike).
Rhine	0·625	—	$\frac{1}{100}$	In Holland.
" flood	—	333	$\frac{1}{1282}$	At Verdingen.

APPENDIX IX.

Compass Bearings and Angles.

		Initials.	Angle.	
			° ′	° ′
0	North	N.	0 0	—
1	North by east	N. by E.	11 15	—
2	North-north-east	N.N.E.	22 30	—
3	North-east by north	N.E. by N.	33 45	—
4	North-east	N.E.	45 0	—
5	North-east by east	N.E. by E.	56 15	—
6	East-north-east...	E.N.E.	67 30	—
7	East by north	E. by N.	78 45	—
8	East	E.	90 0	90 0
7	East by south	E. by S.	101 15	78 45
6	East-south-east...	E.S.E.	112 30	67 30
5	South-east by east	S.E. by E.	123 45	56 15
4	South-east	S.E.	135 0	45 0
3	South-east by east	S.E. by E.	146 15	33 45
2	South-south-east	S.S.E.	157 30	22 30
1	South by east	S. by E.	168 45	11 15
0	South	S.	180 0	0 0
1	South by west	S. by W.	191 15	11 15
2	South-south-west	S.S.W.	202 30	22 30
3	South-west by south	S.W. by S.	213 45	33 45
4	South-west	S.W.	225 0	45 0
5	South-west by west	S.W. by W.	236 15	56 15
6	West-south-west	W.S.W.	247 30	67 30
7	West by south	W. by S.	258 45	78 45
8	West	W.	270 0	90 0
7	West by north	W. by N.	281 15	78 45
6	West-north-west	W.N.W.	292 30	67 30
5	North-west by west	N.W. by W.	303 45	56 15
4	North-west	N.W.	315 0	45 0
3	North-west by north	N.W. by N.	326 15	33 45
2	North-north-west	N.N.W.	337 30	22 30
1	North by west	N. by W.	348 45	11 15
0	North		360 0	0 0

	°	′	″
¼ point	2	48	45
½ "	5	37	30
¾ "	8	26	15
1 "	11	15	0

APPENDIX X.

Marking of the Lead-Line.

Fathoms Deeps.				Fathoms. Marks.	
1	..	..	..	—	
—	..	..	..	2	Leather, with two ends.
—	..	..	..	3	Leather, with three ends.
4	..	..	..	—	
—	..	..	..	5	White calico.
6	..	..	..	—	
—	..	..	..	7	Red bunting.
8	..	..	..	—	
9	..	..	..	—	
—	..	..	..	10	Leather, with a hole in it.
11	..	..	..	—	
12	..	..	..	—	
—	..	..	..	13	Blue serge.
14	..	..	..	—	
—	..	..	..	15	White calico.
16	..	..	..	—	
—	..	..	..	17	Red bunting.
18	..	..	..	—	
19	..	..	..	—	
—	..	..	..	20	Strand, with two knots in it.

APPENDIX XI.

Table showing the Number of Vessels entering the Principal Ports of Great Britain, their Total and Average Tonnage for the Year 1891.

Ports.	Vessels.	Tons.	Average tonnage.
England.			
Barnstaple	3,123	181,990	58·2
Barrow	1,811	470,826	259·9
Beaumaris	5,874	1,227,308	208·9
Boston	596	101,867	170·9
Bridgewater	3,227	190,157	58·9
Bristol	8,158	1,301,544	159·5
Caernarvon	1,606	130,036	80·9
Cardiff	13,383	6,611,768	494·0
Carlisle	621	103,345	166·4
Chester	2,657	178,756	67·[illegible]
Colchester	2,786	156,155	56·0
Cowes	20,905	1,733,337	82·9
Dartmouth	1,103	122,178	110·7
Dover	3,892	960,650	246·8
Falmouth	1,600	212,623	132·8
Faversham	9,093	422,997	46·5
Fleetwood	1,710	487,040	284·8
Folkestone	1,346	263,321	195·6
Fowey	2,105	230,583	109·5
Gloucester	4,126	481,685	116·7
Goole	2,176	596,162	273·9
Grimsby	1,841	760,141	412·8
Hartlepool	2,794	799,456	286·1
Harwich	3,563	702,044	197·0
Hull	5,649	2,590,811	458·6
Ipswich	3,561	261,011	73·2
Lancaster	737	137,573	186·6
Liverpool	17,645	8,623,332	488·7
Llanelly	1,082	173,972	160·8
London	51,632	13,216,946	255·9
Lynn	1,048	180,734	172·4
Maryport	1,242	220,533	177·5
Middlesboro'	3,473	1,405,036	404·5
Milford	1,625	339,984	209·2
Newhaven	1,660	369,648	222·6
Newport	7,966	1,822,554	228·7
Penzance	1,809	227,642	125·8
Plymouth	3,604	781,097	216·7
Poole	1,367	143,230	104·7
Portsmouth	14,328	1,388,646	96·7

Ports.	Vessels.	Tons.	Average tonnage.
England.			
Ramsgate	1,009	171,781	170·2
Rochester	8,433	656,643	77·8
Runcorn	4,196	320,889	76·4
Southampton	10,394	1,764,468	169·7
Stockton	803	203,413	253·3
Sunderland	7,004	2,436,294	347·8
Swansea	5,896	1,343,426	227·8
Teignmouth	735	126,250	171·9
Tyne Ports	16,779	8,054,053	480·0
Weymouth	1,060	164,911	155·5
Whitehaven	2,070	245,610	118·6
Workington	1,599	188,256	117·7
Yarmouth	1,292	158,040	122·3
Scotland.			
Aberdeen	2,799	778,582	278·1
Alloa	1,102	182,066	165·2
Ardrossan	3,119	327,761	105·0
Ayr	2,481	344,753	138·9
Borrowstoness	986	260,457	264·1
Campbeltown	1,146	109,245	95·3
Dundee	1,287	584,862	454·4
Glasgow	9,025	2,711,697	300·4
Grangemouth	2,253	884,707	392·6
Granton	510	238,555	467·7
Greenock	7,977	1,605,559	201·2
Inverness	3,533	451,363	127·6
Kirkcaldy	2,610	757,377	290·1
Kirkwall	2,721	252,506	92·7
Leith	3,749	1,247,769	332·8
Lerwick	862	118,172	137·0
Stornoway	1,427	240,897	168·7
Stranraer	776	154,154	198·6
Troon	2,480	260,518	105·0
Wick	1,107	129,730	117·1
Ireland.			
Belfast	10,304	2,161,155	209·7
Cork	2,858	704,286	246·4
Drogheda	557	128,674	231·0
Dublin	7,496	2,187,859	291·8
Dundalk	687	129,106	187·9
Limerick	550	166,901	303·4
Londonderry	1,611	313,037	194·3
Newry	1,843	270,218	146·6
Waterford	2,030	520,480	256·3
Totals ...	359,650	84,465,198	234·8

APPENDIX XII.

TABLE SHOWING THE NUMBER OF VESSELS BELONGING TO THE UNITED KINGDOM, AND THEIR AVERAGE TONNAGE.

	Vessels.	Tonnage.	Percentage.	
Under 50 tons	4,787	158,082	27·76	—
Of 50 and under 100 tons ...	4,499	319,871	26·09	53·85
„ 100 „ 200 „ ...	1,420	206,908	8·24	62·09
„ 200 „ 300 „ ...	498	123,341	2·88	64·97
„ 300 „ 400 „ ...	354	123,301	2·05	67·02
„ 400 „ 500 „ ...	371	168,459	2·15	69·19
„ 500 „ 600 „ ...	320	176,080	1·85	71·02
„ 600 „ 700 „ ...	317	207,080	1·85	72·87
„ 700 „ 800 „ ...	370	277,766	2·15	75·02
„ 800 „ 1000 „ ...	711	637,359	4·12	79·14
„ 1000 „ 1200 „ ...	799	879,202	4·64	83·78
„ 1200 „ 1500 „ ...	1,123	1,513,564	6·52	90·30
„ 1500 „ 2000 „ ...	1,020	1,751,254	5·92	96·22
„ 2000 „ 2500 „ ...	409	903,348	2·37	98·59
„ 2500 „ 3000 „ ...	168	458,510	0·97	99·56
„ 3000 tons and above ...	77	260,416	0·44	100·00
Totals ...	17,243	8,164,541	100·00	

Average tonnage ... ... 473·5.

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THE END.

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